INTEGRATING CORE AND LOG DATA BY USING DIFFERENT SATURATION HEIGHT FUNCTIONS (SHF)

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CERTIFICATION OF APPROVAL

INTEGRATING CORE AND LOG DATA BY USING DIFFERENT SATURATION HEIGHT FUNCTIONS (SHF)

by

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MAY 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(NEGAR HADIAN NASR)

ABSTRACT

Log and core analysis are 2 main sources to characterize the reservoir. Logging provide information in wider interval compare to the core but it has limitation due to log measurement and interpretation. Core samples provide more accurate result for certain depths and it need to upscale to analyze the saturation result in wider interval.

Well logging and data obtained from core analysis are usually combined together to determine initial saturations of the fluids in the reservoir. Measurements of capillary pressure is considered one of the main data of the core analysis. Capillary pressure measurement indicates the volumetric behavior of fluids of the reservoir in static condition in the reservoir rock. In the case of prior knowledge of the level of free water and with the availability of capillary pressure data, one can restore initial water saturation in the reservoir. Saturation-height functions (denoted by, SHF) used in this study to integrate the result of saturation from core and log.

Saturation-height function has got a huge effect on reserves in place calculations. SHF can predict reservoir fluid saturation at a chosen height from the level of free water and it's widely utilized by both petrophysicist and reservoir engineers.

This project, reviews the performance of 3 different SHF on seven different wells of an Iranian oil field:

- J-Leverett function
- Pseudo-J function
- Lambda function

The advantages and disadvantages of each method highlighted. All the 3 functions tested by examining how accurately they can model the saturation-height of a certain wells and the impact on calculation of hydrocarbon in-place. The modification in the methodology used for J-Leverett method and introducing the new SHF as Pseudo-J function were the main objectives of this study. The results shown that Pseudo-J function is the best option for this case study as it give the best match compare to the other two methods.

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CHAPTER 1

1. INTRODUCTION

1.1 Background study

Core analysis is an experimental procedure includes conducting experiments on core plugs obtained from a reservoir. Core analysis is a measurement of core sample obtained from well to extract certain facts and parameters from the reservoir. These parameters lately can be used as an input data to computer simulation (Eclipse, Petrel RE) for visualizing the reservoir behavior. It also use as an initial source of data for field management and development planning from initial discovery to appraisal and mature field development. It also used to calibrate with wireline log for determining the volume of reserve. This core analysis normally related to petro-physicist work but it is also can be used for other discipline such as reservoir engineering, production technology for well injectivity and also important for geologist.

1.1.2 Capillary Pressure

From the measurements of different core samples of rocks with heterogeneity, one can generate capillary pressure curves which reflects the permeability and porosity of the core samples. It means cores from a single individual well but from different rock parts produce curves that reflects permeability and porosity of the specific core.

Interaction between fluids and rock is reflected by the capillary pressure, it is dependent strongly on the geometry of the rock pores, wettability and interfacial tension (Sohrabi et al., 2007). Equation 1.1, illustrate the relationship between capillary pressure with fluid and rock properties.

$$\mathrm{Pc} = \frac{2\sigma\cos\theta}{\mathrm{r}} \tag{1.1}$$

Where:
r: radius of pore
σ: Interfacial tension
θ: The contact angle.

Fluid densities control oil and water pressure gradient. Distribution of water saturation on top of FWL (or under FWL with negative capillary pressure) is influenced by the equilibrium of buoyancy and capillary forces (difference of density and gravity) (B. Harrison et al., 2001).

Equation 1.2 show capillary pressure equation in oil-water system (B. Harrison et al., 2001):

$$\mathrm{Pc} = (\rho_{w-}\rho_o)\mathrm{gh} \tag{1.2}$$

Capillary pressure can be calculated using oilfield unit: Pressure in psi, height in feet to the reference FWL and densities of fluid given in lbm/ft3 (B. Harrison et al., 2001).

$$\mathrm{Pc} = \frac{\mathrm{h}(\rho_{w-}\rho_o)}{144} \tag{1.3}$$

In terms of pressure gradient, equation 1.3 can be expressed as follows (B. Harrison et al., 2001):

As the fluid pressure gradient=$\rho/144$

$$\mathrm{Pc} = \mathrm{h}(\text{water gradient} - \text{oil gradient}) \tag{1.4}$$

Thus, by the knowledge of the capillary pressure function, water saturation at a specific height can be calculated. It’s indicate that accurate estimation of Pc is significant in reserve estimation.

Equation 1.5 shall be used to adjust capillary pressure measured in laboratory to the capillary pressure inside the reservoir (Sohrabi et al., 2007).

$$(\mathrm{Pc})_{\mathrm{res}} = \frac{(\sigma\cos\theta)_{\mathrm{res}}}{(\sigma\cos\theta)_{\mathrm{lab}}}(\mathrm{Pc})_{\mathrm{lab}} \tag{1.5}$$

Where:

θres /θlab : Reservoir/lab contact angle
σres /σlab : Reservoir/lab interfacial tension

In most of the cases, reservoir rocks are heterogeneous and the Pc measurements are not sufficient to determine all sorts of variations in the properties of the rocks. Specially, when using lab data to express the field data, scaling the petrophysical properties of the rock become significant. In this case consideration of the geometry of the pore spaces (denoted by (2/r) in the equation 1) is very important (Sohrabi et al., 2007).

Interfacial tension (IFT) between two immiscible fluids which occupying the same core sample, create the pressure difference that called capillary pressure.

$$\mathrm{Pc} = \mathrm{P_{nw}} - \mathrm{P_w} \tag{1.6}$$

$$\mathrm{P_{cow}} = \mathrm{P_o} - \mathrm{P_w} = \sigma_{\mathrm{ow}}\left(\frac{1}{\mathrm{R1}} - \frac{1}{\mathrm{R2}}\right) \tag{1.7}$$

Where:

σow: interfacial tension between oil and water

R1 and R2: radius of curvature

Knowing the capillary pressure is important because of the following reason:

- Prediction of initial saturation distribution in the reservoir
- Prediction of free water level (FWL)
- Prediction of fluid contact in reservoir (WOC)
- Prediction of rock properties (permeability)
- Calculate pore size distribution

Oil-water Contact (OWC)

The starting depth in the reservoir where a 100% water saturation exist. Water saturation is 100% and Pc = Pd.

$$OWC = \frac{P_d}{\Delta \rho} \tag{1.8}$$

Where;
OWC: Oil water contact, ft
Pd: Displacement pressure, psi
$\Delta\rho$: oil and water density difference

Transition Zone

The vertical thickness over which water saturation ranges from 100% to irreducible water saturation.

Oil Pay zone (clean oil zone)

The zone above the upper demarcation line of the transition zone. In this zone oil production is water free.

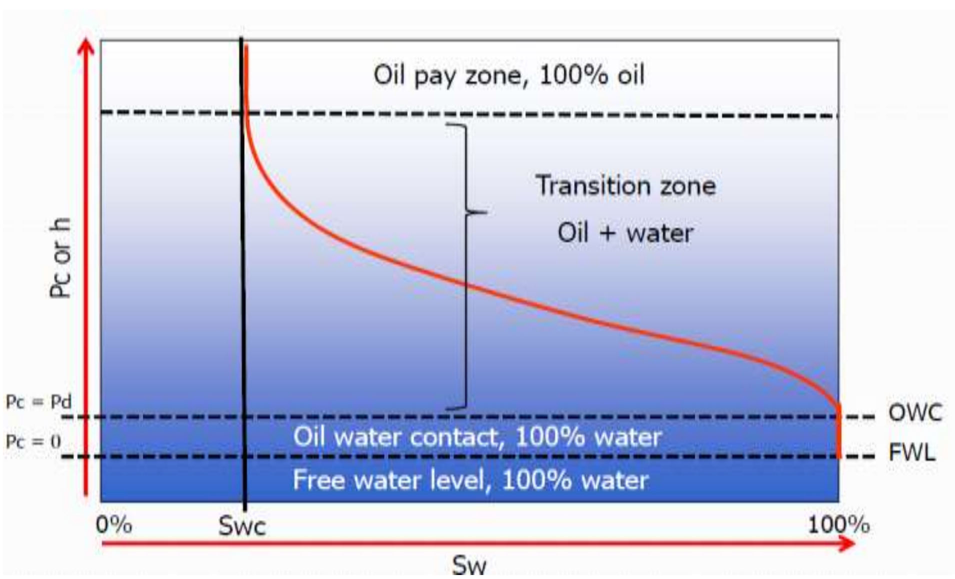


Figure 1.1: Initial saturation distribution in reservoir (Puan Mazuin, 2011)

1.1.3 Capillary Pressure Measurement Methods

There are 3 different type of measurement method for capillary pressure: Mercury method, Porous-Plate method & Centrifuge method

Mercury methods

Mercury methods are widely used for irregular shape(originate in the drill cutting).In this method, the sample will surrounded by mercury and the pressure gauge will showing the variation in pressure with respect to the volume of mercury that enter the irregular sample. It is for estimating porosity from volume of mercury inside the sample. Capillary pressure curves of the mercury can be obtained within an hour or more, and its highly depends on the permeability of the irregular sample.

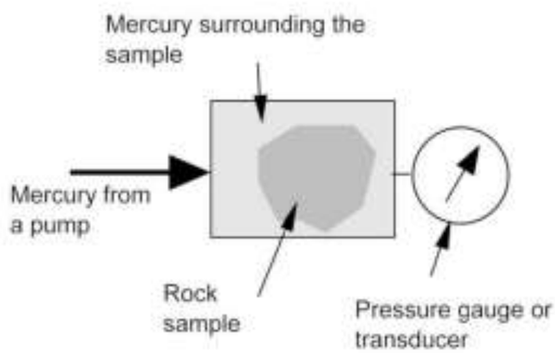


Figure 1.2: Mercury method (Purcell. 1949)

Porous-plate methods

The porous-plate method will give very accurate Pc by using a cylindrical sample. In this measurement method the chamber occupied with gas and the rock sample saturated with water. By increasing the pressure of the gas, water will be displaced with the force of the gas inside the sample. It means gas replace with water. When displacement stops, the capillary pressure can be found by difference between the gas pressure around the sample and the saturated water pressure remain in the lower side of the sample.

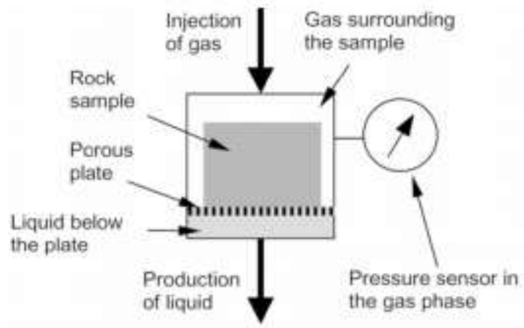


Figure 1.3: Porous-Plate method (Christoffersen et. al 2001)

<u>Centrifuge methods</u>

Cylindrical sample initially saturated with oil then it's put in a centrifuge, and is rotated and by the time the spinning rate will increases. The centrifugal forces cause the oil to leave the sample while absorbing surrounding gases inside the sample. In term of time, it's not as fast as mercury method but it's faster than porous-plate method.

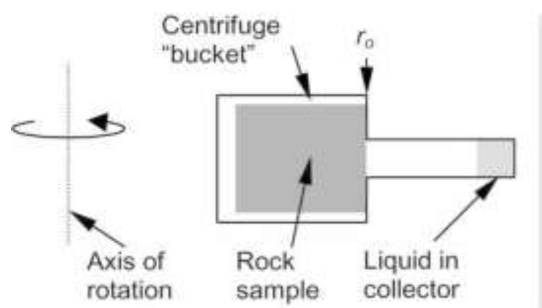


Figure 1.4: Centrifuge method (Ruth and Chen., 1995)

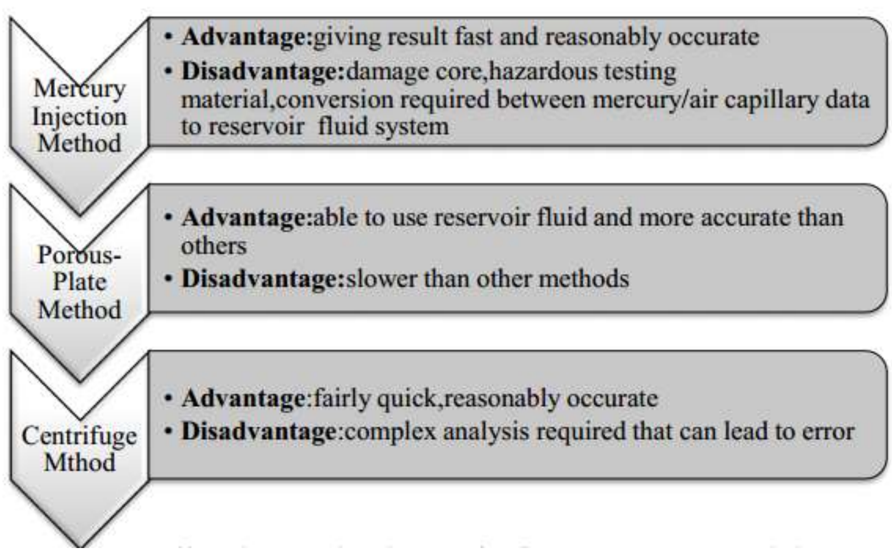


Figure 1.5: Advantage and Disadvantages of capillary pressure measurement methods

1.1.4 Surface/ Interfacial tension

- Surface tension (ST): describing the gas-liquid surface forces
- Interfacial tension (IFT): characterizing the interfacial forces of two immiscible fluids (liquid-liquid force)

In oil and water system, water and oil do not mix with each other because water molecules form a hydrogen bonds which results in a very high IFT. Both oil and water have high IFT. Adhesion between them is weak so they cannot mix.

<u>Wettability</u>

It's defined as the relative adhesion between two fluids with the solid surface. It is so important because it influence the distributions of oil, gas and water within reservoir rock. As well it affects capillary pressure and relative permeability &Production of hydrocarbon.

Assume surface tension with this symbol(γ). Each surface tension perform like its interface, and define the angle θ at which the liquid phase contacts the surface. This is identified as the wetting angle of the liquid to solid in the existence of the gas. Young's equation (1805) proposed equation 1.9:

$$\gamma_{lg} \cos\theta = \gamma_{sg} - \gamma_{sl} \tag{1.9}$$

$$\text{If } \gamma_{sg} > \gamma_{sl}\text{, then } \cos\theta > 0 \text{ and } \theta < 90^o$$
$$\text{If } \gamma_{sg} < \gamma_{sl}\text{, then } \cos\theta < 0 \text{ and } \theta > 90^o$$

Where;
γ_{lg}: Surface tension between liquid and gas
γ_{sg}: Surface tension between solid and gas
γ_{sl}: Surface tension between solid and liquid

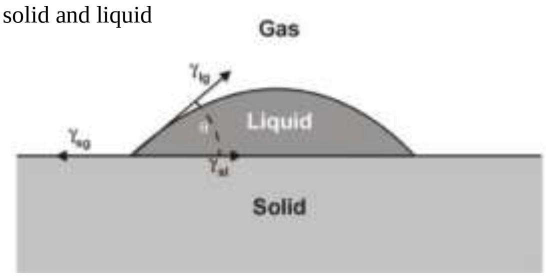


Figure 1.6: liquid/gas & solid wetting angle (Paul Glover, 1964)

Adhesion tension (AT) is Spreading tendency of fluid or in other word it controls which fluids favorably wets the solid.

$$A_T = \underbrace{\sigma_{So}}_{\text{IFT between lighter fluid and solid}} - \underbrace{\sigma_{Sw}}_{\text{IFT between denser fluid and solid}}$$

$$\cos\theta_{ow} = \frac{\sigma_{so} - \sigma_{sw}}{\sigma_{ow}}$$

$$A_T = \sigma_{ow}\cos\theta_{ow} \tag{1.10}$$

Table 1.1: Contact angles and interfacial tension for common fluid-fluid interfaces (Paul Glover, 1964)

Interface	Contact Angle, θ, degrees	$\cos\theta$	Interfacial Tension, dynes/cm
Air-Water	0	1.0	72
Oil-Water	30	0.866	48
Air-Oil	0	1.0	24
Air-Mercury	140	-0.765	480

1.1.5 Drainage and Imbibition

There are 2 different types of testing which are results of displacement in two-phase flow in porous media. These two test called imbibition and drainage tests. Drainage test happen when a non-wetting fluid displaces a wetting fluid. The opposite case defines the imbibition test. In the laboratory first the core saturated with the wetting phase (water) then by injecting non-wetting phase (oil), displaces the water to minimum level (connate water). This process called drainage and it’s considered to initiate the initial fluid saturations of the reservoir when it’s exposed. By reinjecting the water into the core, the wetting phase which is water increases continuously. This process is called imbibition.

1.1.6 Log Interpretation

Recording the geophysical parameter like porosity, resistivity, density and etc. versus depth in a borehole produces the well logs that is significant in finding a hydrocarbon reserves. The goal of well logging and log interpretation is to find the type of hydrocarbon exist in the formation by providing the certain measurement. There are three different type of logging:

- Electrical (Spontaneous Potential, Resistivity)
- Nuclear (Gamma Ray, Density, Neutron)
- Sonic/acoustic (Transit time)

Interpretation steps

For interpretation purpose there are 3 types of basic logs need to be used in term of formation evaluation**.** Each of these logs is located in specific track in order to evaluate it easier and faster.

1) **Permeable zone logs** (GR, SP, Caliper): this log used to differentiate between the clean sand (sandstone) and shale reservoir. Usually low value of gamma ray (GR) or spontaneous potential (SP) indicates clean sand while the opposite case indicates the shale. Usually this log presented as the first track and it used to indicate the quality of the rock.

2) **Resistivity logs** (Medium, Deep and Shallow resistivity logs): after finding the clean sand zone, the next step is to find the hydrocarbon by using resistivity log. Higher resistivity shows more hydrocarbons in reservoir, it can be in low or high porosity. However low resistivity is showing more water in to system.

3) **Porosity logs** (Neutron, Density and Sonic**):** this log used to see variation of the porosity profile with resistivity. High porosity followed by low resistivity specifies water or shale. Low porosity with high resistivity specify oil zone.

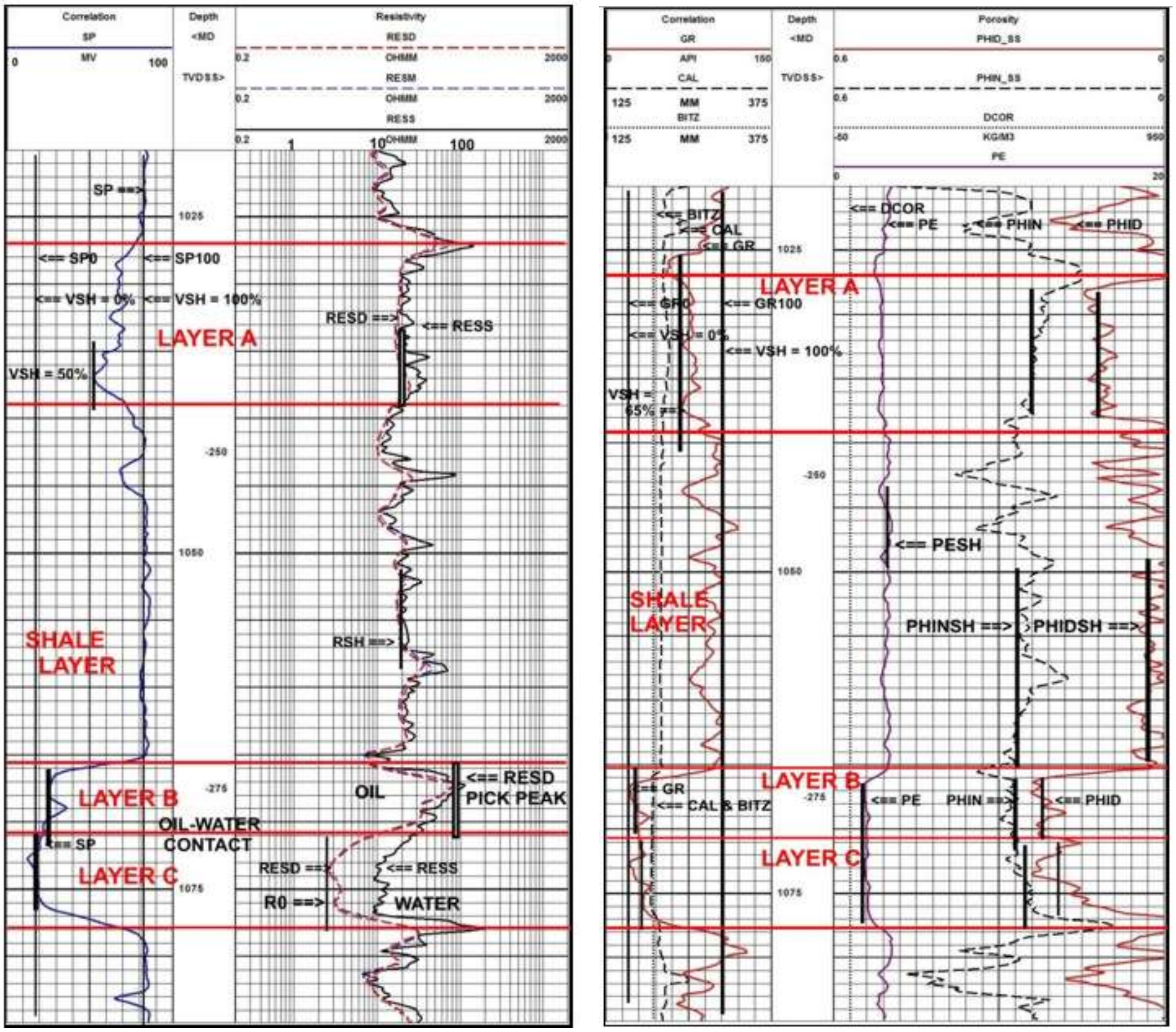


Figure 1.7: Permeable zone logs, Resistivity logs and Porosity logs (Crains, 1984)

Oil/water contact can be recognized by resistivity log and mostly it's shown when the resistivity is in the lowest value in the clean and porous reservoir. In this point the water saturation (SW) first reaches to its maximum near to 100%. When saturation water is almost 100%, we have free water level (FWL) which contains only water. Mostly in this project, the author focus on depth above free water level so finding these points from the well logs is significant.

1.1.7 Field overview

The selected field for this study is located in South part of Iran. It is an oil producing reservoir. This reservoir divided into four compartments. The study has been done on seven wells that distributed in different segments as north segment, center west, center east and south west. The wells distribution in this field is as follow:

Segment North: E2-W5 and E2-P5
Segment center east: E1-P4 and E2-W7
Segment south west: E3-P4
Segment center west: S6 and S2

Reservoir engineers define 4 bins for this reservoir based on four different lithology types. Experiment has been done on 36 core sample and Capillary Pressure data obtained by using mercury-air measurement method.

1.2 Objectives

- Evaluate the saturation estimated by using three different saturation height functions (SHF) for an Iranian oil field.
- Enhance the performance of three SHF methods applied in this study by improving the methodology used for each of them.

1.3 Problem statement

Data quality control is crucial to reservoir engineers. Having more sets of saturation data verifies the accuracy of volumetric calculation. However, it is essential to consider the limitations in log measurements and their interpretation of each logs. One of the main issue with conventional electrical logs is bad resolution in thinly bedded formations (laminations take place within less than 1m in interval). Other complications include the influence of the water imbibition processes, clay excess conductivity, mud filtrate invasion and determining of the Archie saturation exponent “n” that is wettability dependent during imbibition process (B. Harrison, 2001).

However, considering only core samples wouldn't be enough to represent the whole reservoir since cores are taken from specific depths only and it need to be upscale in order to represent the dynamic behavior of the reservoir. In addition, cores usually are not preserved properly and are changed from their original state by the time they reach to the laboratory.

In order to estimate the correct saturation variation through the reservoir depth, core and log data should be integrated together. However this integration is sensitive to lots of parameters that need to consider while calculating the saturation. In the recent days reservoir engineers can utilize data received from core analysis by the use of different saturation height functions.

1.4 Scope of study

In this project, performance of three different saturation-height functions (J-Leverett, Lambda and Pseudo-J functions) are evaluated for an Iranian oil field. These three methods were tested on 7 different wells to investigate the best method for the selected field. Necessary modification is done in the methodology used for each SHF, to improve the performance of each method. These methods were used mainly by reservoir engineers in order to calculate new saturation variation from capillary pressure data taken from cores and compare the result with the saturation variation from log. The advantages and disadvantages of each method are shown.

CHAPTER 2

2. LITERATURE REVIEW

2.1 Saturation-Height function (SHF)

There are few type of saturation height approaches which use capillary pressure records data from different core sample from varies depth to generate saturation variation versus height above free water level (HAFWL). SHF is a useful method, in order to compare the core with log result and having better and more accurate hydrocarbon in-place estimation.

This study evaluates three different saturation-height functions (J-Leverett, Lambda and Pseudo-J) which used in oil and gas industry.

2.1.1 J Leverett Function

Leverett in 1941 proposed a formula with respect to Pc that this formula depends on a permeability and porosity ratio as $\left(\frac{K}{\emptyset}\right)^{0.5}$.

This formula consider the total pore geometry to be constant means consider universal curve for the whole reservoir. However the variation of wettability, porosity and the permeability of the reservoir are important in J-function formula. If the reservoir system show different rock types and significant alteration in porosity and permeability, then this method may not give so accurate result.

$$. J = \frac{Pc}{\sigma \cos\theta} \sqrt{\frac{K}{\emptyset}} \qquad (2.1)$$

Where:

Pc: Capillary pressure at different wetting saturation (Psi)
σcos θ: Interfacial tension and cosine θ of oil/gas-water
k: Rock permeability (md)
Ø: Rock porosity (fraction)

In this method, capillary pressure vs saturation data for all the samples is converted to the J-function using equation 2.1. All of the J functions curves converted to the single curve to represent the whole reservoir. These procedure called normalizing the Pc curve by using J-formula (B Harrison, 2001). Based on the curve fitting of all the J-function and Pc curve, the Sw can be generated using equation 2.2. Aj and Bj are the equation constants which can vary based on different reservoir binning.

$$Sw = A_j J^{Bj} \tag{2.2}$$

Based on the literature survey, Leverett J – Function initially used to convert all capillary pressure to a universal curve. However, this curve didn’t give a sufficient result due to variation of rock type. Different rock carries different properties like permeability and porosity or wettability which can affect the capillary pressure curves (B. Harrison, 2001).

J-Leverett is a widely used method that usually applied in the industry. However based on the studies that has been done on this method, J-Leverett function cannot effectively applied on the reservoir with various rock types. This feature of J Leverett method make it less accurate while calculating saturation variation for different part of reservoir with different rock parameters such as porosity and permeability. Leverett J is used to normalize the capillary pressure data from given rock type of a reservoir. In some similar cases, this function can be used by different reservoirs with the same rock type, but extreme attention required in order avoiding any error (Sohrabi et al., 2007, B. Harrison, 2001).

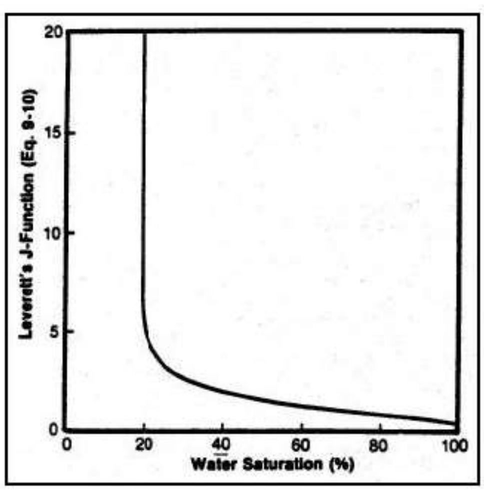


Figure 2,1: Leverett-J function (Henry L, 1960)

2.1.2 Lambda – Function

Al-Bulushi (2009) stated that Lambda function is flexible and more complex compare to the other methods. It is a good way to match the saturation data which is hard to fit with other relationship. In the function of lambda, it is assumed that the main water saturation predictor is either porosity or permeability variation and it depends on the reservoir structure and properties. From the fitting analysis of porosity and permeability curves, A_L and B_L variables which are regression constants can be obtained.

By considering equation 1.4 and the relationship between water saturation and HAFWL, equation 2.3 and 2.4 generated for lambda function.

$$\lambda = \frac{\log(\frac{A_L}{Sw - B_L})}{\log \mathrm{HAFWL}} \tag{2.3}$$

$$Sw = A_L * HAFWL^{-\lambda} + B_L \tag{2.4}$$

Where:

AL & *B*L & λ: Lambda function constants (calculated from curve fitting)

HAFWL: height above free water level

2.1.3 Pseudo J – Function

It's consider one of the best method that apply in the industry. Pseudo J function is not as famous as the other two methods mentioned above and it didn't use in literature. It consider as one of the new and the best method that use power concept in its calculation. Pseudo-J function currently use by reservoir engineers in certain companies. The information provided here is by the author internship experience.

$$\mathrm{Pc} = \mathrm{A_p Sw^{B_p}} \tag{2.5}$$

$$Sw = \sqrt[B]{A_p} * Pc^{-\frac{1}{B_p}} \qquad (2.6)$$

Ap & Bp: Pseudo-J function constants (calculated from curve fitting)

By combining equation 1.4 and equation 2.6, the equation 2.7 can be generated:

$$SW = A_p * HAFWL^{B_p} \qquad (2.7)$$

Sohrabi (2007) stated that there is a way to elaborate on the accuracy of each method. They proposed using some error indicator equation to visualize and analyze the error encounter from each function. The goal of using these equations is to make the comparison between saturation obtained from cores and logging for each SHF. Equation 2.8 is showing average absolute percentage deviation (AAD%) and equation 2.9 is used to find the standard error of estimate.

$$ADD\% = \frac{\frac{\sum_{j=1}^{n} |\,(Sw_{core} - Sw_{Logging})\,|}{Sw_{Logging}}}{n} * 100 \qquad (2.8)$$

$$SEE = \sqrt{\frac{\sum_{j=1}^{n} [\,(Sw_{core} - Sw_{Logging})\,]^2}{n-1}} \qquad (2.9)$$

Sw(logging) and Sw(core) represent the values obtained from logs and cores analysis.

CHAPTER 3

3. METHODOLOGY

Before starting any project and involving in any part of this study, the background study of a field is essential in order to have a better overview in the nature of a project. Revision of the reservoir engineering and geological documents of the model and other related reports and articles have contributed to solve the errors and confusion which usually occur during project solving process. The project involves the following activities that should be done by the student during FYP1 and FYP2.

3.1 Project activities

- Literature survey:
    - Capillary pressure and its measurement methods
    - Wettability and its calculation technique
    - Drainage and Imbibition process
    - Log interpretation
    - SHF
- Consideration of problems during project solving process
- Extended proposal preparation
- Data gathering and data preparation (selected an Iranian field as an case study)
- Proposal defence
- Data evaluation and data quality control
- Preparing Interim report
- Coding the three SHF methods (J-Leverett, Lambda and Pseudo-J function) into Excel
- Test all the three SHF on 7 different wells for the selected Iranian field
- Being familiar with the concept of reservoir binning and apply it in the project
- Evaluate the saturation estimated by using three different saturation height functions (SHF) and comparison with the saturation from logging.

- Enhance the performance of three SHF methods applied in this study by improving the methodology used for each of them.
- Select the best SHF which give the best match
- Submission of progress report
- Calculate the absolute deviation and error encountered from each method for both fields
- Pre-sedex
- Final report submission
- Viva
- Submit final report(Hard-bound)

3.2 SHF calculation procedure

3.2.1 Pseudo-J method

- Adjust laboratory measured capillary pressure for the fluid properties and the effects of wettability in comparison to the conditions inside the reservoir using equation 1.5.
- Plot capillary pressure curve for all the 36 core samples.
- Use equation 2.5 and find the Ap and Bp from each Pc curve by using the power law-curve fitting (result 36 Ap and 36 Bp).
- Use the porosity histogram in figure 4.4 for reservoir binning and divide it into different sections base on porosity variation.
- Plot 36 Ap and 36 Bp values vs porosity.
- Find Pseudo-J constants (Ap and Bp) for each reservoir bin by using equation 2.6.
- By using equation 2.7,calculate saturation variation vs HAFWL
- Compare the results with log saturation and try to get the match
- Calculate ADD% and SEE for all the seven wells.

3.2.2 J-Leverett method

The following procedure is used to convert the Pc curve to J-function curve:

- Select some values of water saturation (Sw) in the range of 0-1 and read the corresponding values of capillary pressure curves which are the function of permeability, saturation and porosity.
- By considering equation 2.1, multiply the Pc by sqrt (k/phi) and divide by σcosθ using the values in table 1.1 with respect to the interface (since we are dealing with oil and water reservoir system σcosθ is 48.
- Generate poro-perm curve and get the best trendline equation by curve fitting
- After computing and plotting J-function curve, Get an average J curve by averaging poro-perm value. The unique J curve is representative for all the capillary curves generated.
- Find the J-Leverett constants Aj and Bj from the single J curve vs Sw.
- Using J-Leverett constants, to generate the saturation vs HAFWL for the all the 7 wells.
- Using the LAS files (simulator input) in order to get logging information such as saturation, porosity, permeability and well specification for each well. (LAS file is prepared by geologist and it use Archie equation to compute saturation from resistivity log)
- Evaluate and compare the saturation calculated from J-Leverett method with saturation form logs (taken from the LAS file).
- Introduce the modified J-Leverett function by improving the performance of J-Leverett method (improving its methodology).
- Considering different J-function curve for different reservoir bins based on the lithology types.
- Compute new constants (Aj and Bj) for different reservoir bins by using rock quality index (RQI) and average porosity and permeability.
- By using equation 2.2, calculate the saturation for each reservoir bin with different Aj and Bj.

- Using modified J-Leverett constants, to generate the saturation vs HAFWL for the all the 7 wells.
- Compare the performance of J-Leverett and modified J-Leverett method.
- Calculate ADD% and SEE for all the seven wells.

3.2.3 Lambda method

- Calculating A and B constants from each capillary pressure curve using equation 2.5.
- Calculating height above free water level by subtraction oil water contact from true vertical depth (HAFWL= OWC- TVD).
- Combine the 36 capillary curves into 4 Pc curves.
- Find connate water saturation (Swc) for 4 new Pc curves.
- Calculating lambda(λ) from equation 2.3.
- Plotting constants (A_L , B_L and λ) vs permeability and porosity
- Get the best trendline from the curve fitting
- Divide the reservoir into 4 groups based on the permeability and porosity
- Calculate the lambda constants (A_L, B_L and λ) for each groups.
- Calculate Sw from lambda function by using equation 2.4 and compare with Sw log.
- Calculate ADD% and SEE for all the seven wells.

3.3 Project Flowchart

The following flowchart shows the procedure of the study which are required to be completed for this project.

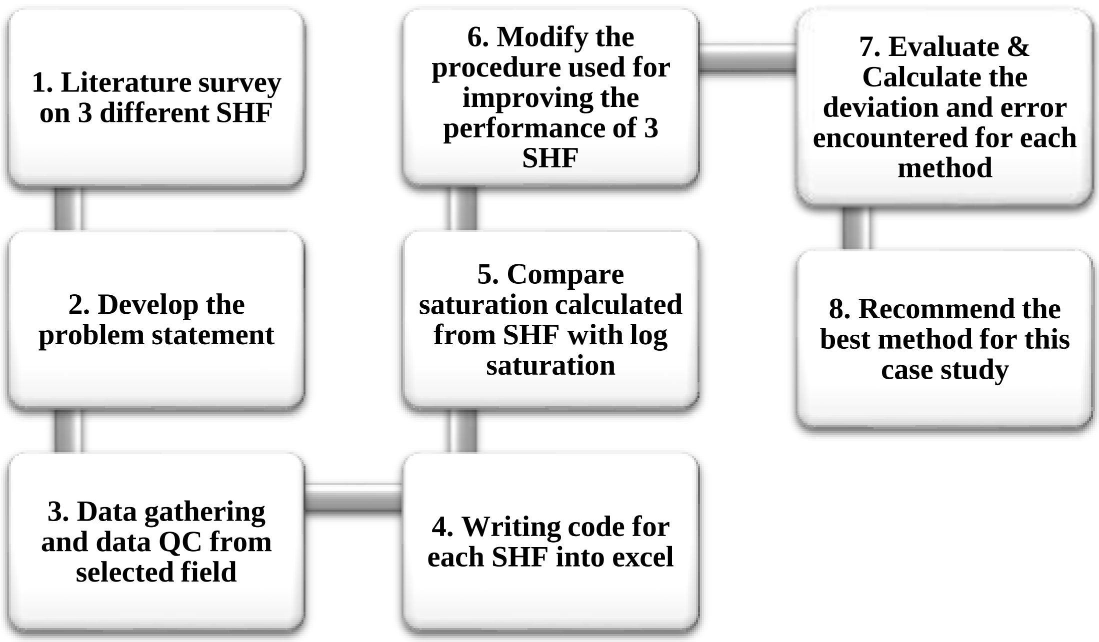


Figure 3.1: Project flowchart

3.4 Key Milestone and Gantt chart (FYP 1 & FYP 2):

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Selection of project topic														
Background study & research on different SHF														
Submission of Extended Proposal														
Data gathering and data QC														
Proposal Defence														
Improving literature about the project, do research about the working procedure & findings														
Writing Interim Report														
Submission of interim report to supervisor and coordinator														
Semester break														
Code writing in excel														
Compare and match saturation calculated from SHF with log saturation for a specific field														
Submission of Progress Report														
Test SHF created, on different field and compare the results between 2 fields														
Poster Presentation														
Final Report Submission														
Viva														
Project dissertation														

CHAPTER 4

4. RESULT AND DISCUSSION

The purpose of this project is to prepare the different SHF models and try to test them on real field data. Comparing the result of different methods and modifying some properties in order to get better match is highlighting in this report.

One of difficulties that author faced in this project is having very low connate water saturation (Swc). Fine clay structure which invaded the pore spaces of the core sample will destroy caused by high surface tension of mercury. These clay structure control the pore throat diameter and their destruction affect permeability. The destruction of fine clay structure would result in less irreducible water saturation (Swir) in the core measurement as compare to the reservoir (Hill et al., 1979).

Pseudo J – Function

As stated in the literature, each capillary curves are a function of porosity, permeability and saturation based on the different core samples. To adjust capillary pressure measured in laboratory to the capillary pressure inside the reservoir the equation 1.5 mentioned in background study will be used. In this study $\sigma resCosres$ and $\sigma labCoslab$ are 26 and 42 dyne/cm as it proposed in the litreture (Sohrabi et al., 2007).

$$(\mathrm{Pc})_{\mathrm{res}} = \frac{(\sigma\cos\theta)_{\mathrm{res}}}{(\sigma\cos\theta)_{\mathrm{lab}}}(\mathrm{Pc})_{\mathrm{lab}}$$

Where:

$(\sigma cos\theta)_{res}$=26 dyne/cm

$(\sigma cos\theta)_{lab}$=42 dyne/cm

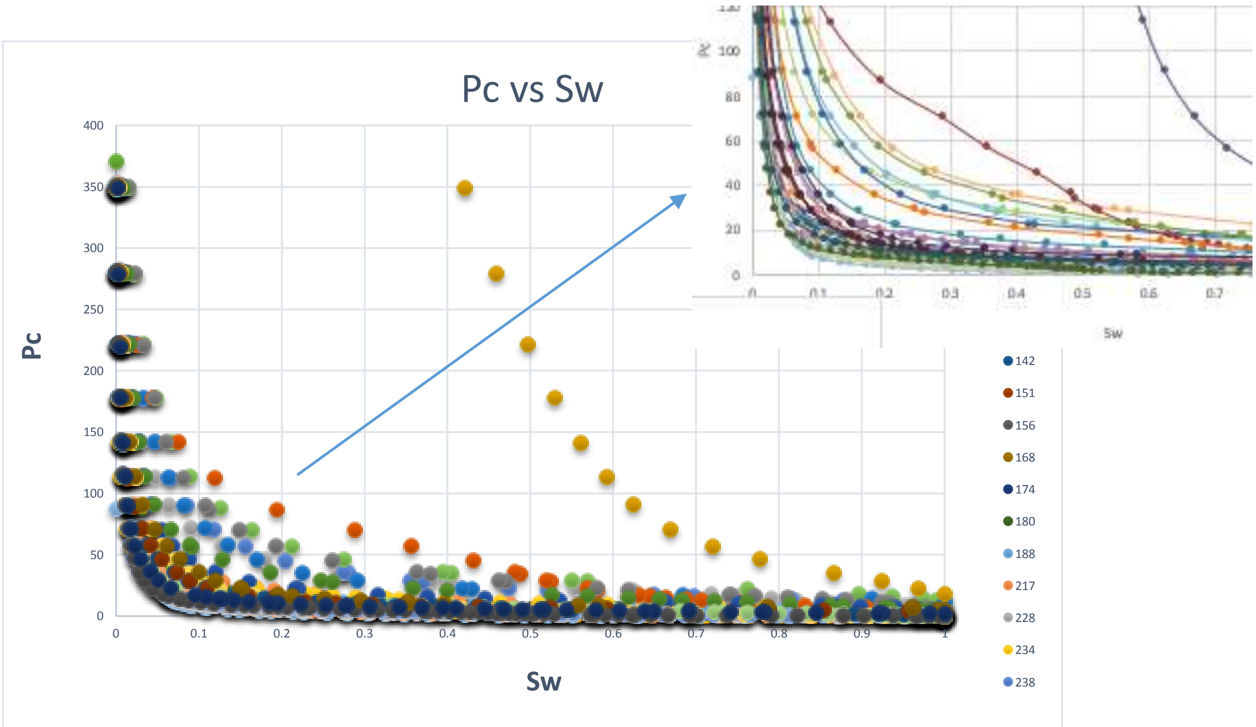


Figure 4.1: Capillary pressure curves for 36 core samples

Equation 2.5 used to find the pseudo-J constants. From each capillary pressure (Pc) curve as it shown in figure 4.1, A_p and B_p can be generated which are the functions of porosity. Normally the power low give the best match for Pc curves (Sohrabi et al., 2007). Equations 4.1 and 4.2 are generated from curve fitting.

$$\mathrm{A_p} = 0.234\emptyset^{-1.36} \tag{4.1}$$

$$\mathrm{B_p} = -1.038\emptyset - 0.8268 \tag{4.2}$$

Figures 4.2 and 4.3 show the Ap and Bp versus porosity variation. From these figures and figure 4.1, table 4.1 generated.

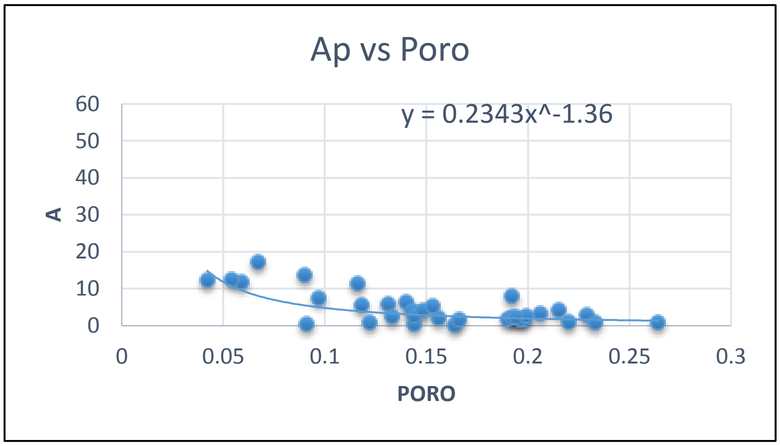


Figure 4.2: Ap vs porosity for each core sample

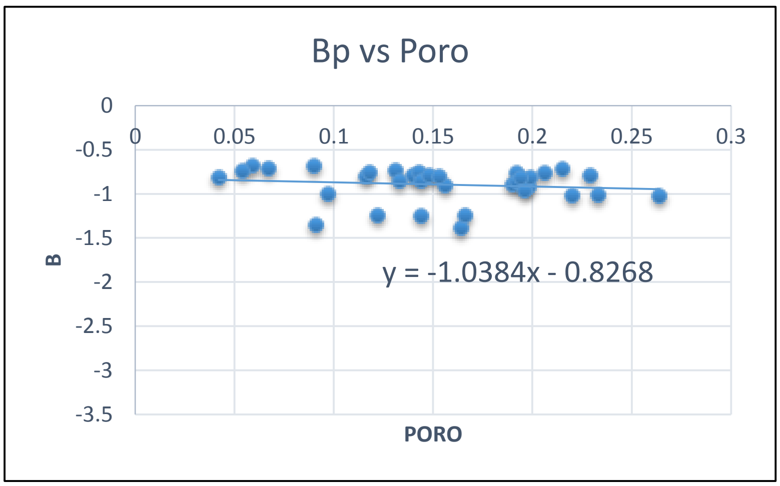


Figure 4.3: Bp vs porosity for each core sample

Table 4.1 shows Ap, Bp and porosity for all the 36 core samples. In addition the depth that each sample were taken shown in this table.

Table 4.1: Ap and Bp for all the 36 core samples

samples	Depth	Ap	Bp	porosity
1	2483	12.354	-0.81	0.042
11	2845.5	11.493	-0.802	0.116
26	2849.29	46.108	-1.691	0.145
33	2851	6.4881	-0.793	0.14
36	2851.75	8.0308	-0.764	0.192
38	2852.32	0.2666	-1.387	0.164
39	2852.5	0.4724	-1.349	0.091
40	2852.75	0.4706	-1.247	0.144
48	2854.75	0.9416	-1.24	0.122
50	2855.25	1.0285	-1.016	0.22
53	2856	1.883	-0.892	0.19
66	2859.25	7.5774	-0.998	0.097
72	2860.75	4.2126	-0.756	0.143
75	2861.5	0.9244	-1.021	0.264
78	2862.25	5.9406	-0.733	0.131
82	2863.25	3.0188	-0.787	0.229
84	2863.75	3.3181	-0.758	0.206
95	2866.5	15.881	-3.319	0.186
98	2867.25	1.6957	-1.245	0.166
103	2868.56	0.9575	-1.012	0.233
113	2871	1.735	-0.919	0.198
127	2874.5	2.1705	-0.902	0.156
140	2877.75	2.5225	-0.854	0.133
142	2878.25	2.2002	-0.856	0.192
151	2880.5	2.8474	-0.851	0.144
156	2881.92	1.6676	-0.96	0.196
168	2884.75	2.7877	-0.809	0.199
174	2886.25	2.3988	-0.81	0.194
180	2887.75	4.1168	-0.787	0.148
188	2889.75	4.2832	-0.714	0.215
217	2897	5.601	-0.755	0.118
228	2899.75	11.9	-0.68	0.059
234	2901.25	5.4506	-0.798	0.153
238	2901.75	12.595	-0.742	0.054
252	2905.75	17.272	-0.707	0.067
280	2912.75	13.871	-0.684	0.09

The next step is to define the classes based on porosity range. As it's shown in the porosity histogram (Figure 4.4).

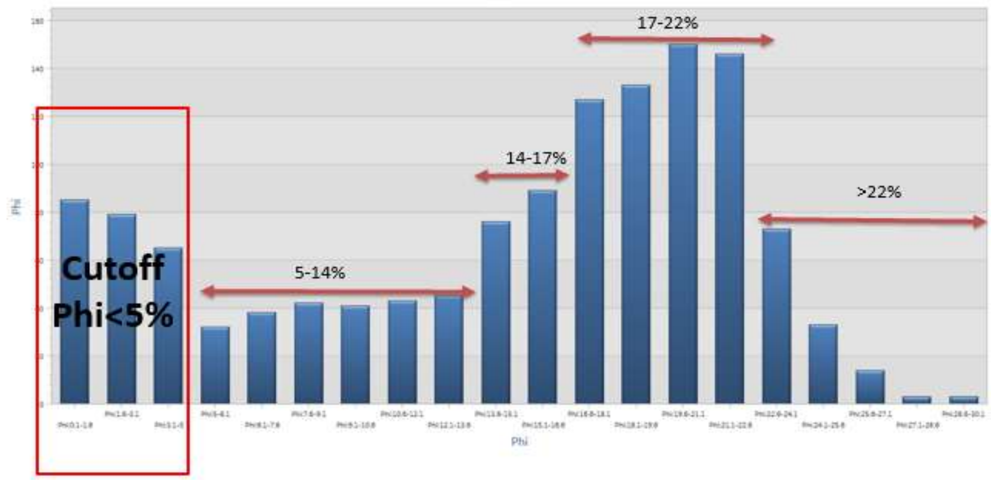


Figure 4.4: Reservoir binning based on porosity histogram

Table 4.2 shows the finalize Ap and Bp for new grouping system. Based on the figure 4.4, there are four reservoir bins. By this definition, four sets of constants generated as follow:

Table 4.2: Computing Constants Ap and Bp for different porosity groups

Classes	Porosity Bins	Avg porosity	Ap	Bp	$\sqrt[B]{A_p}$	$\frac{1}{B_p}$
Cut off	0<Por<0.05	0.025	35.36502	-0.85276	65.45685074	-1.1726
1	0.05<Por<0.14	0.095	5.755303	-0.925448	6.626703834	-1.0805
2	0.14<Por<0.18	0.155	2.957476	-0.987752	2.997509321	-1.0124
3	0.17<Por<0.23	0.2	2.091084	-1.03448	2.040296434	-0.9666
4	0.23<por>0.3	0.265	1.426126	-1.101976	1.380041823	-0.9074

Figure 4.5 is the (LAS) file for one of the well in this case study. This file created by geologist after evaluating and analyzing the gamma ray, resistivity, SP and porosity logs. (LAS) file contains all the necessary information about the well such as depth interval, porosity, permeability and water saturation (calculated by using Archie equation from resistivity log) along with well interval. Creating (LAS) file is not in the scope of this study.

```
# LAS format log file from PETREL
# Project units are specified as depth units
#==================================================================
~Version information
VERS.   2.0:
WRAP.   NO:
#==================================================================
~Well
STRT .m       2700.1864000 :
STOP .m       2822.3188000 :|
STEP .m      0.15240000 :
NULL .         -999.250000 :
COMP.               : COMPANY
WELL.  Well E1-P     : WELL
FLD.                : FIELD
LOC.                : LOCATION
SRVC.               : SERVICE COMPANY
DATE.  2015-04-08 07:52:21    : Log Export Date {yyyy-MM-dd HH:mm:ss}
PROV.               : PROVINCE
UWI.        : UNIQUE WELL ID
API.                : API NUMBER
#==================================================================
~Curve
DEPT .m                       : DEPTH
SWE .                         : SWE
PHIE_CAPE .m3/m3              : PHIE_CAPE
~Parameter
#==================================================================
~Ascii
2700.6956       0.182300001     0.122750998
2700.848        0.168899998     0.123989999
2701.0004       0.143299997     0.135261998
2701.1528       0.123300001     0.141389996
2701.3052       0.104699999     0.147552997
2701.4576       0.0911          0.149707004
```

Figure 4.5: (.LAS) file sample for one of the wells for field A

After calculating Ap and Bp for different bins, water saturation can be calculated for each depth in the range of the well interval by use of core and SHF. In this study our concern is to compute water saturation for transition zone. It means water zone is neglected and height above free water level is significant for Saturation-heights methods. In this study water gradient and oil gradient assumes to be 0.433 and 0.27 respectively.

$$Sw = \sqrt[B]{A_p} * Pc^{-\frac{1}{B_p}}$$

$$P_c = \text{HAFWL (water gradient – oil gradient)}$$

$$Sw = A_p * HAFWL^{B_p}$$

Table 4.3 shows the HAFWL, PC and SW (Pseudo-j) for one of the well for this field.

Table 4.3: Computing HAFWL, PC and SW (Pseudo-j) for well E1-P

TVDss(m)	TVDss(ft)	poro	Sw Log	Classes	OWC(m)	HAFWL(m)	PC(psi)	Sw (Pseudo-J method)
2791.678	9159.497	0.152277	0.0573	2	2900	92.3216	49.37387	0.057844788
2791.831	9159.997	0.152196	0.0585	2	2900	92.1692	49.29236	0.05794162
2791.983	9160.497	0.148224	0.062	2	2900	92.0168	49.21086	0.058038775
2792.136	9160.997	0.143725	0.0664	2	2900	91.8644	49.12936	0.058136255
2792.288	9161.497	0.137737	0.0719	1	2900	91.712	49.04785	0.098738161
2792.44	9161.997	0.137951	0.0746	1	2900	91.5596	48.96635	0.098915761

Figures 4.6, 4.7, 4.8, 4.9, 4.10, 4.11 and 4.12 provided in this section displaying the water saturation from the logs and saturation calculated from the core samples by using the Pseudo J method for seven wells in this reservoir.

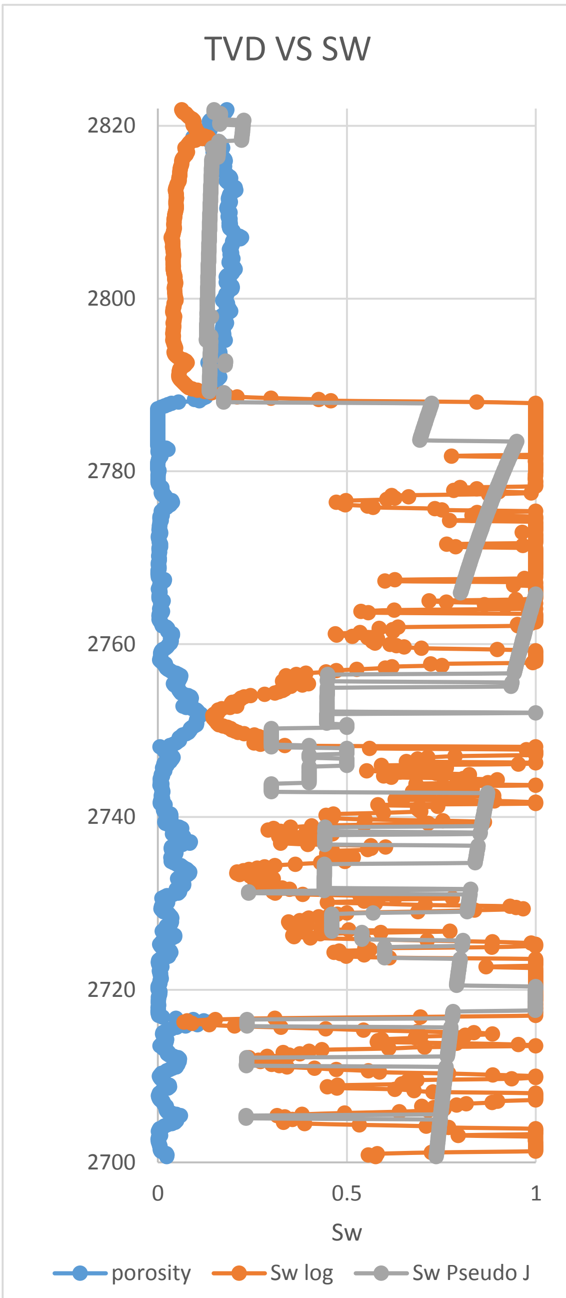


Figure 4.6: Well E1-P4

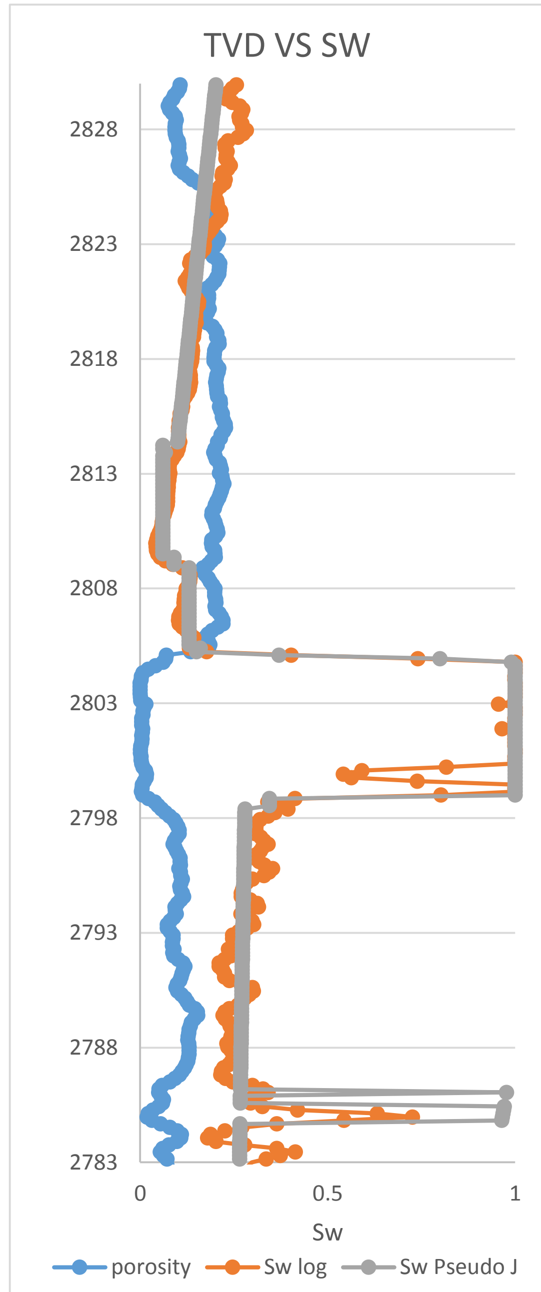


Figure 4.7: Well E2-P5

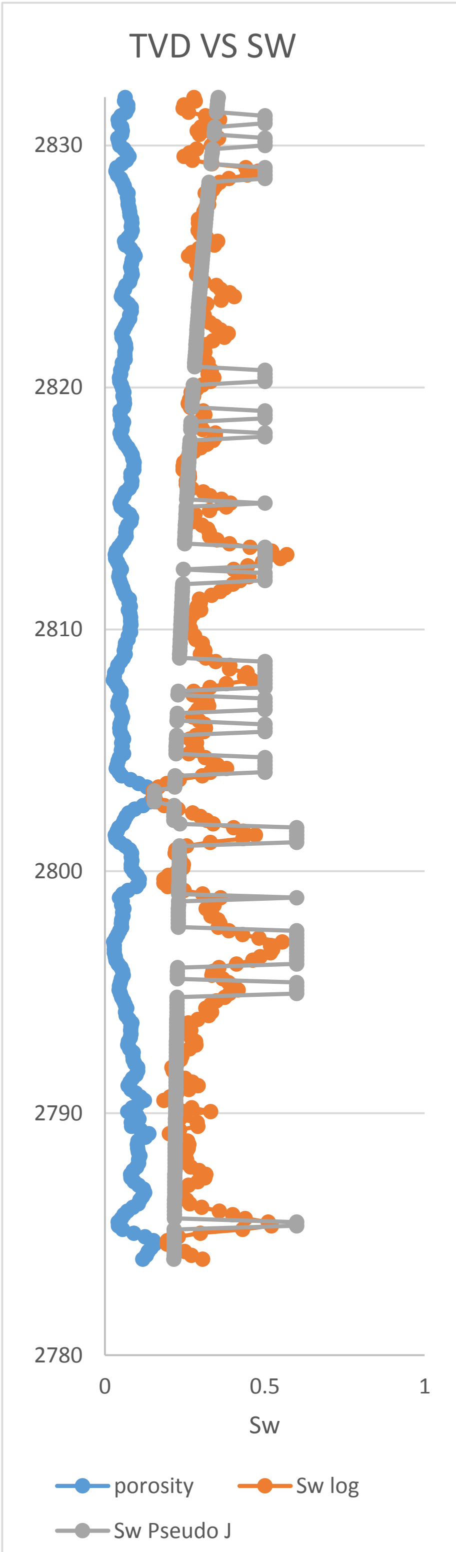


Figure 4.8: Well E2-W5

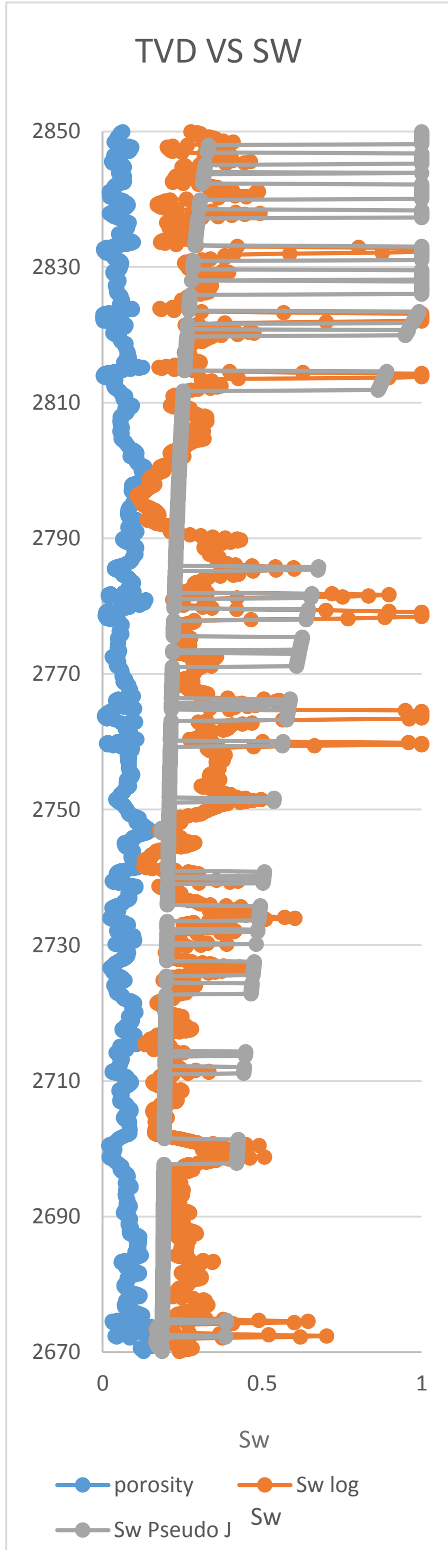


Figure 4.9: Well E2-W7

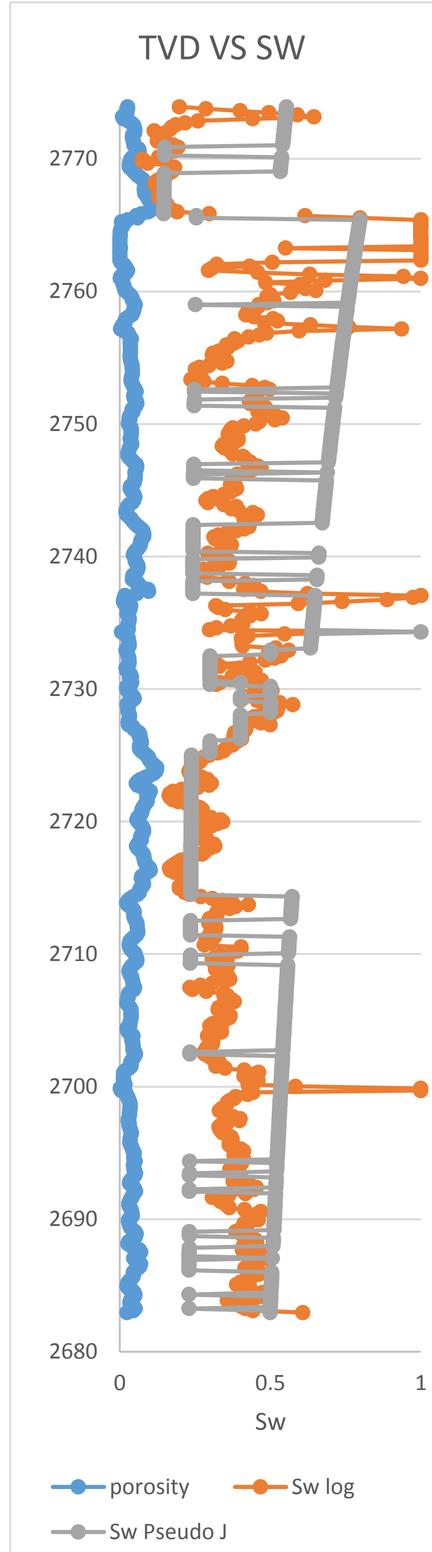


Figure 4.10: Well S2

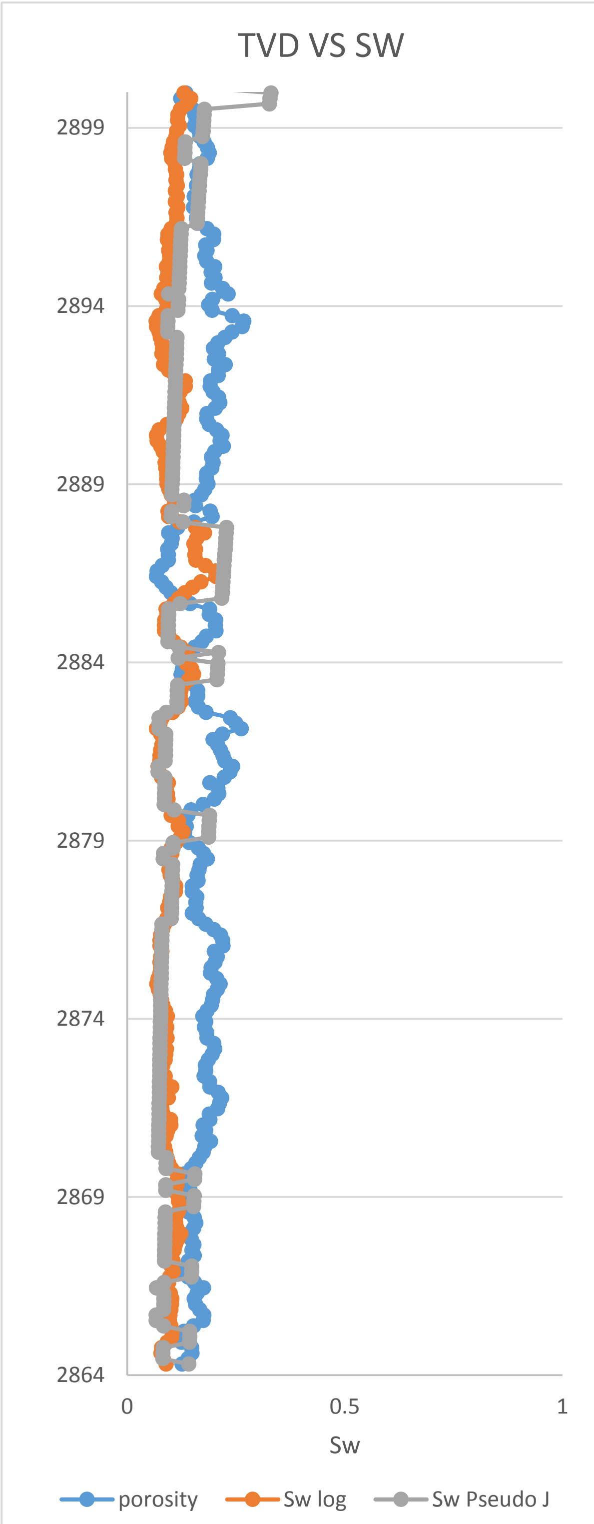


Figure 4.11: Well E3-P4

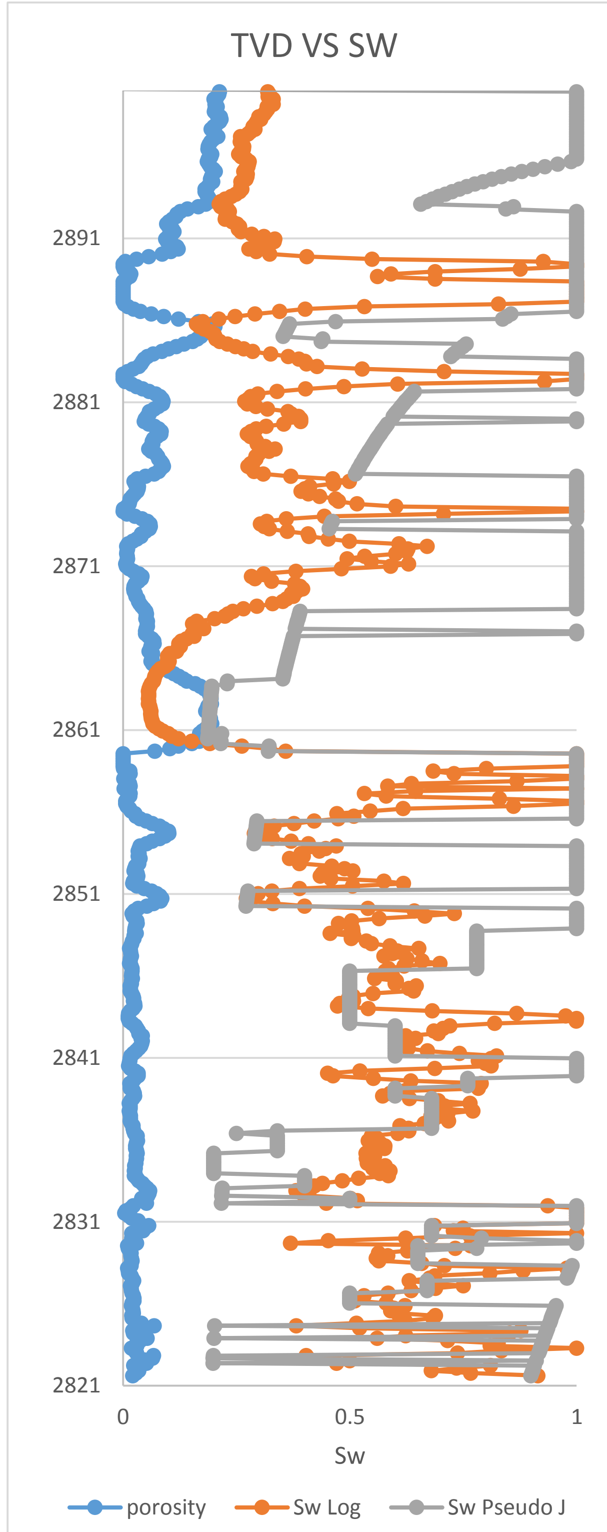


Figure 4.12: Well S6

J Leverett Function

As stated in the literature, J Leverett method convert all the capillary pressure curves into the single J function curve. Capillary pressure versus saturation data for all the samples are changed to the J function using the formula provided below. Then all of the J functions curves will be converted to the single curve.it called normalizing the Pc curve by using J-formula.

Initially the author was tried to convert all capillary pressure to a universal curve. But, this curve didn't give a sufficient result due to variation of rock types. Different rock carries different properties like permeability and porosity or wettability, which can affect the capillary pressure curves. Figure 4.13 shows the J function curves for all the 36 core samples. Figure 4.14 shows the poroperm relation for the whole reservoir system.

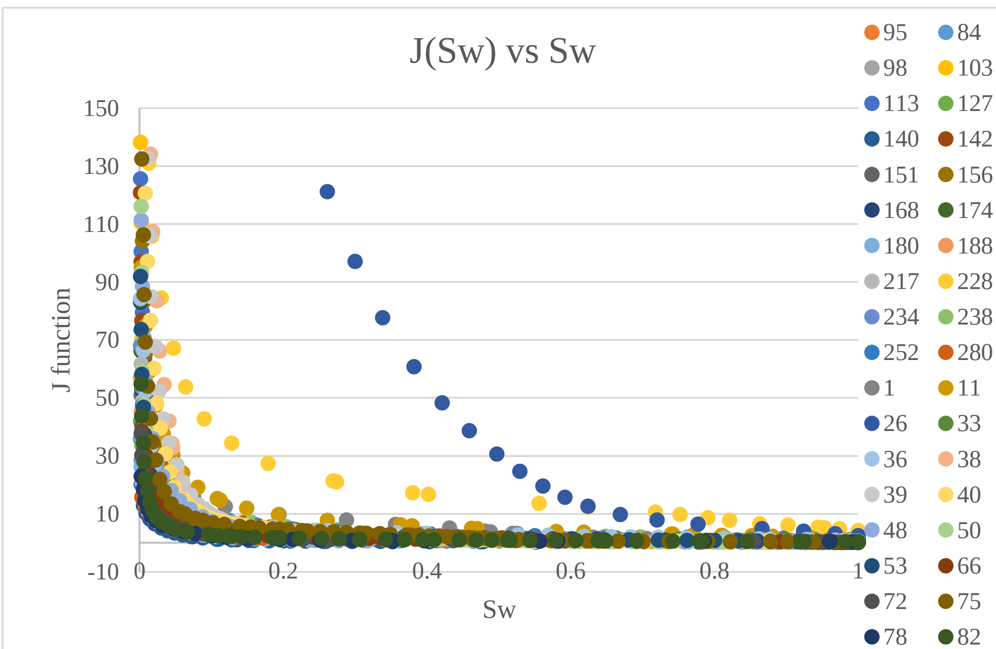


Figure 4.138: J function curves for 36 core samples

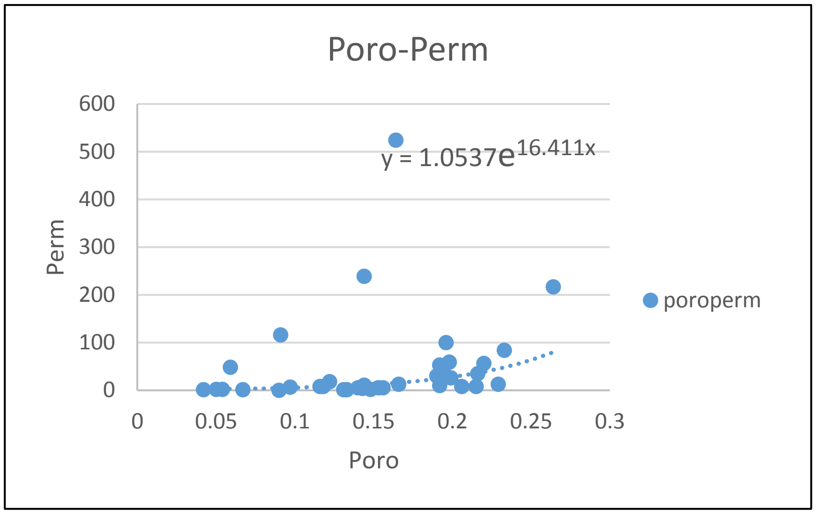


Figure 4.14: Permeability vs porosity curve resulting from core measurement

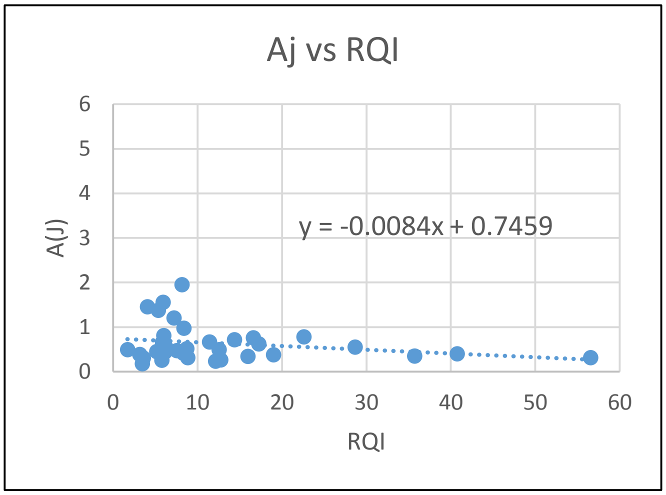
Amaefule (1993) introduce the use of rock quality index (RQI) as it shown in equation 4.3. In J-Leverett method variation of porosity and permeability is significant. RQI is used to define the reservoir bins while using J-Leverett method.

$$RQI = 0.0314\sqrt{\frac{k}{\emptyset}} \quad (4.3)$$

Table 4.4: Porosity, permeability to air, RQI and Aj & Bj for J leverett function (not all the samples are presented)

samples	Depth (m)	porosity	Kair (md)	RQI	Aj	Bj
1	2483	0.042	1.2	5.345224838	1.3757	-0.81
11	2845.5	0.116	7.7	8.147349897	1.9508	-0.802
26	2849.29	0.05	2.2	6.633249581	0.5582	-1.691
33	2851	0.14	5	5.976143047	0.8078	-0.793
36	2851.75	0.192	10	7.216878365	1.2074	-0.764
38	2852.32	0.164	524	56.52540978	0.3139	-1.387
39	2852.5	0.091	116	35.70329501	0.3514	-1.349
40	2852.75	0.144	239	40.73968854	0.3994	-1.247
48	2854.75	0.122	18	12.14664495	0.2383	-1.24
50	2855.25	0.22	56	15.9544807	0.3418	-1.016

Table 4.4 shows the data required and calculated from each core sample for J-Leverett method and figure 4.15 shows the J Leverett constants (Aj and Bj) versus rock quality index.



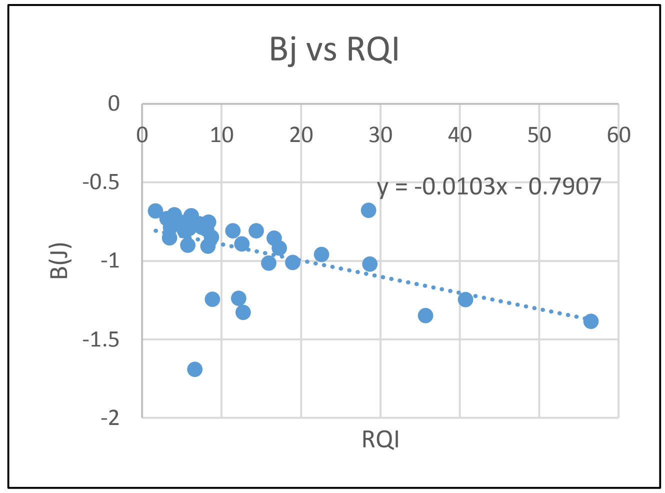


Figure 4.15: Aj & Bj (J function) vs RQI

$$Aj = -0.0084RQI + 0.745 \tag{4.4}$$

$$Bj = -0.0103RQI - 0.7909 \tag{4.5}$$

Then based on RQI the best curve which match with other J function curves will be chosen to be a representing curve for the whole reservoir. Figure 4.16 is showing the single averge J function curve. By use of this curve and its constants Aj and Bj, saturation vs height for each well can be calculated.

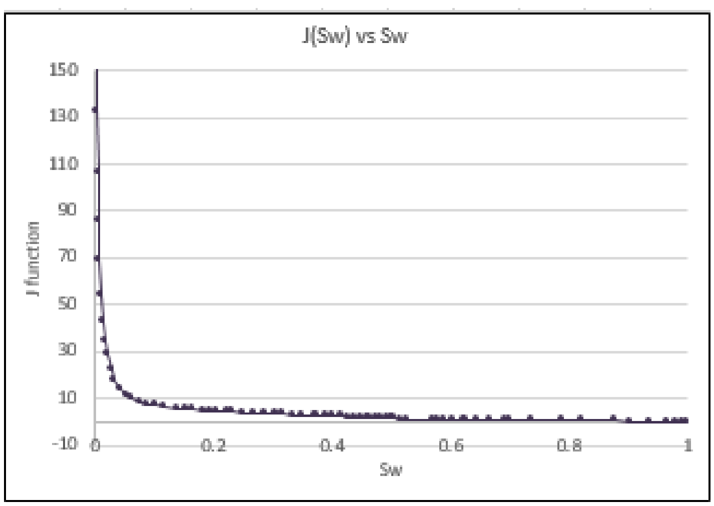


Figure 4.16: Single J function curve that represent the whole reservoir

The result of saturation vs height that taken from a single curve j function doesn't give a very good match and it's because of variation in rock types in this reservoir. Different rocks have different properties like permeability and porosity. So the result cannot be so accurate if a single curve with the specific permeability and porosity is representing the whole reservoir. For getting the better match between Sw log and Sw calculated from core, the author recommend to modify the J-leverett function by considering different curve for each reservoir bins. In this study, 4 different J function curves generated as there are 4 different reservoir groups based on porosity histogram. The results of this modification shown in table 4.5. Figure 4.17 shows modified J function curves.

Table 4.5: J-Leverett constants for four different reservoir bins

Classes	Aj	Bj	Avg porosity	Avg perm	RQI
1	5.755303	-0.92545	0.095	5.009584	7.261711781
2	2.957476	-0.98775	0.155	13.41016	9.301460872
3	2.091084	-1.03448	0.2	28.06457	11.84579374
4	1.426126	-1.10198	0.265	81.55053	17.54245804

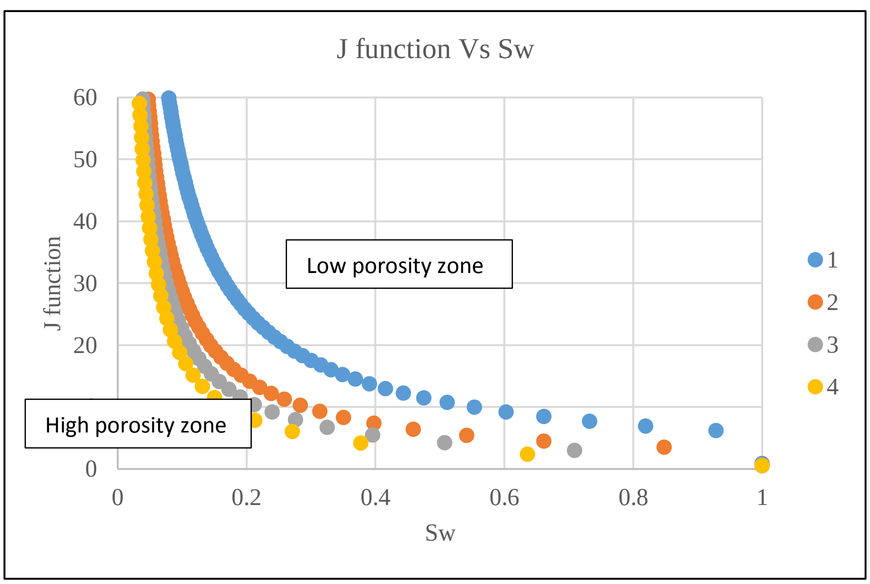


Figure 4.17: Modified J function curve

Figures 4.18, 4.19, 4.20 and 4.21 compare the result from J-Leverett with modified J-Leverett function for well E2-W5 and E2-W7. It is clear from these figures that modified J-Leverett provide better match since it's consider different curves for different bins. After this the modiefied J-Leverett use for the other wells. Figures 4.22, 4.23, 4.24, 4.25 and 4.26 are showing the results for well E2-P5, E3-P4, S2, E3-P4, S6 and E1-P4 using modified J-Leverett function.

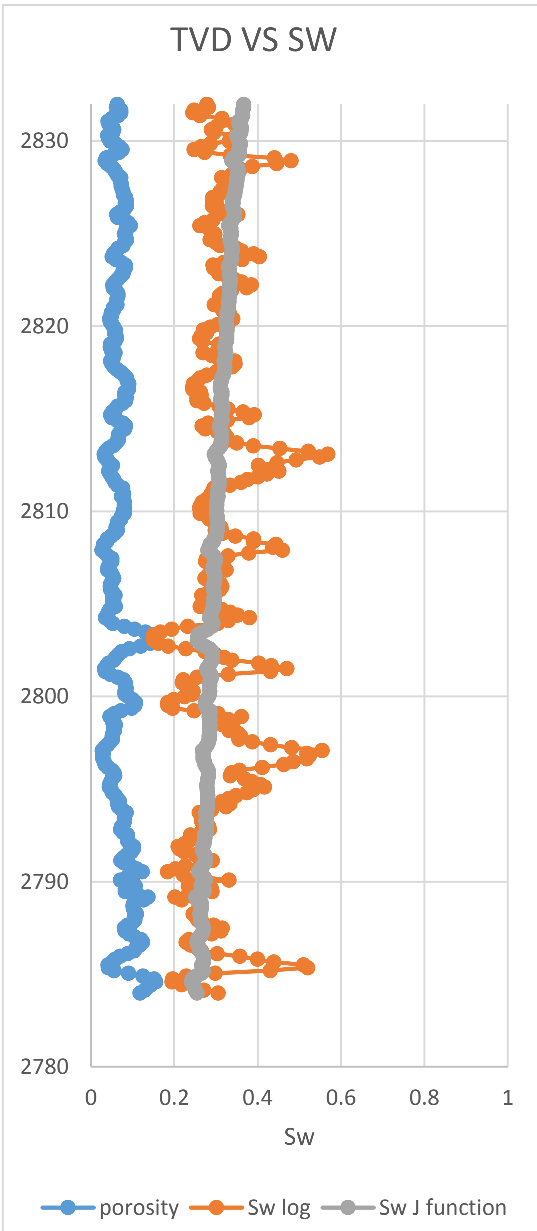


Figure 4.18: Well E2-W5 (single curve J function)

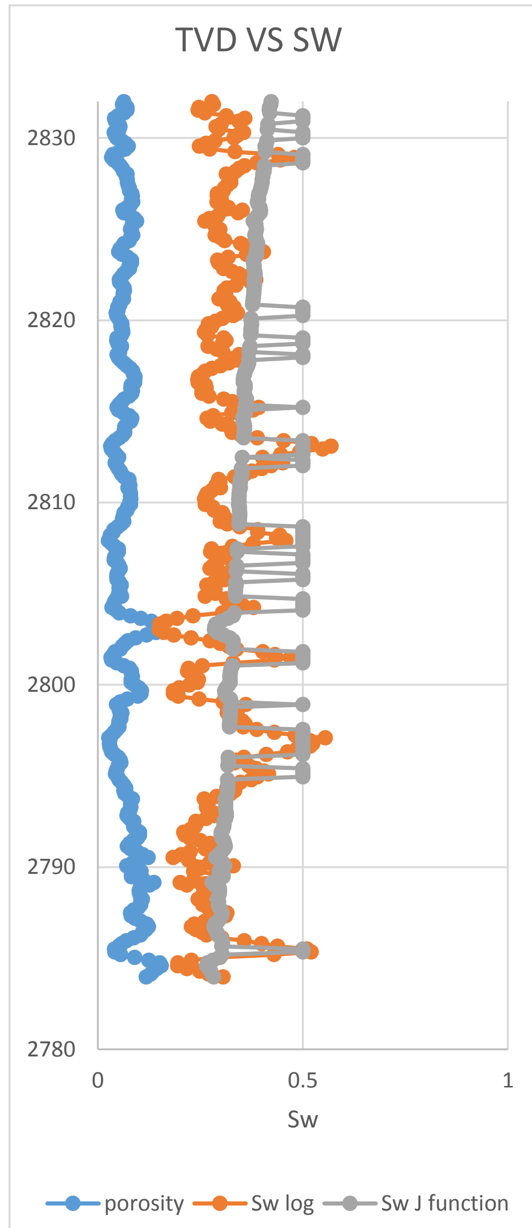


Figure 4.19: Well E2-W5 (Modified J function)

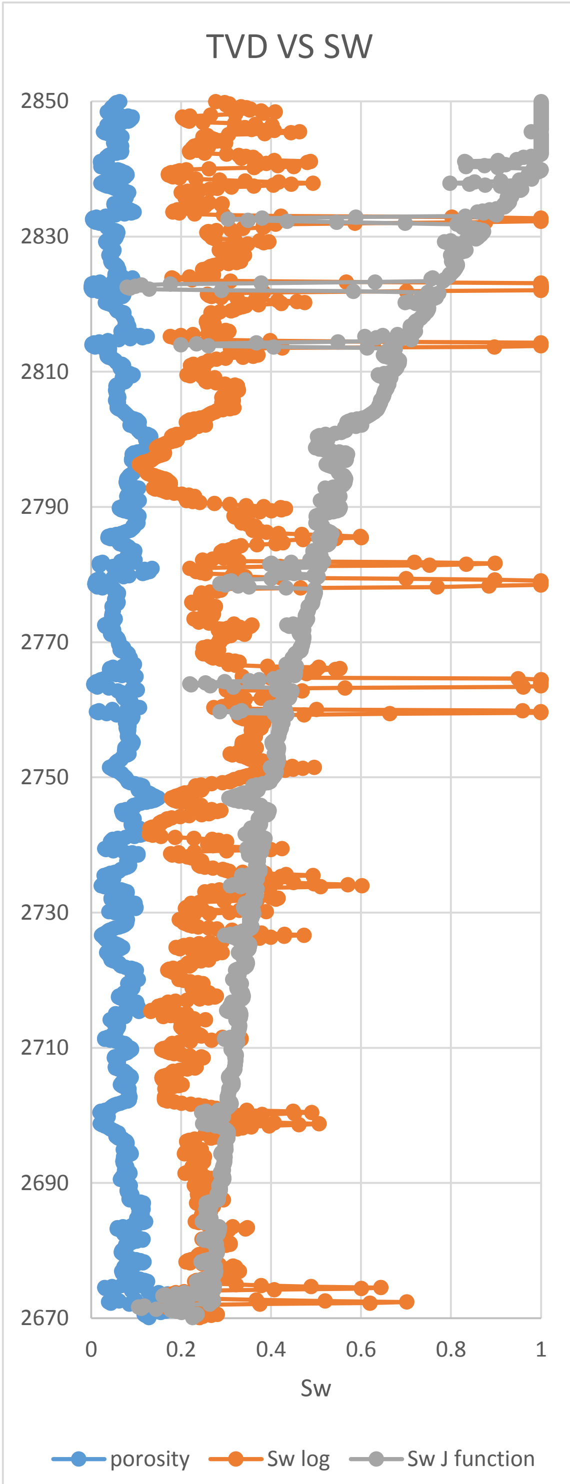


Figure 4.20: Well E2-W7 (single curve J function)

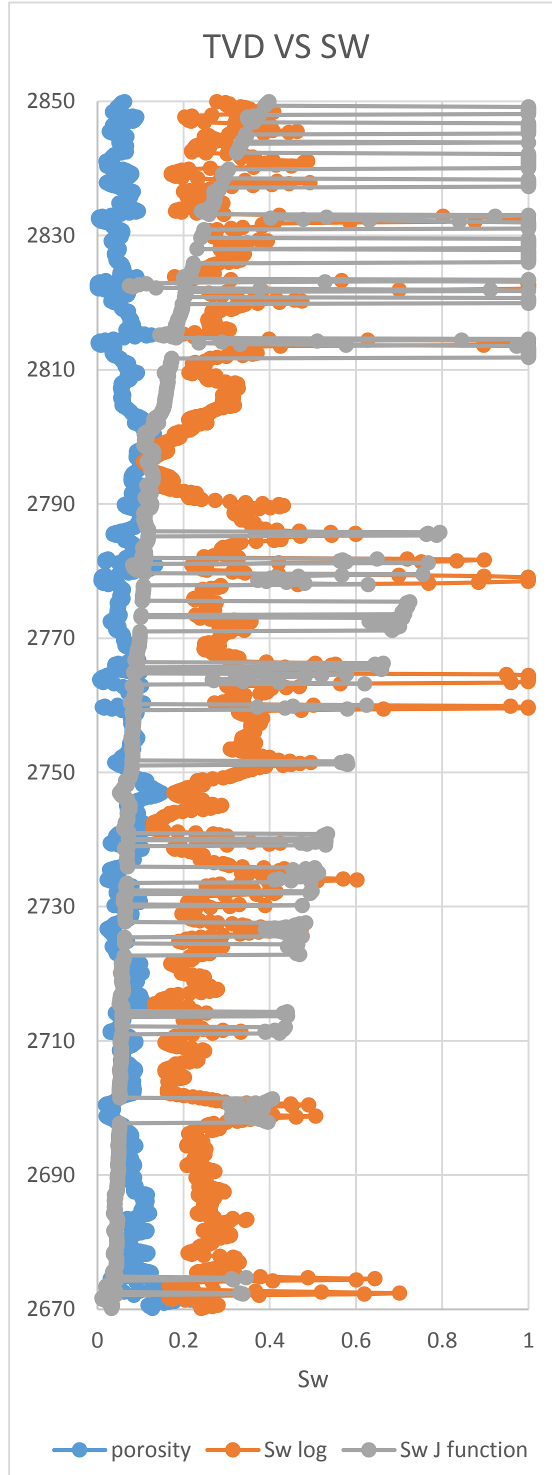


Figure 4.21: Well E2-W7 (Modified J function)

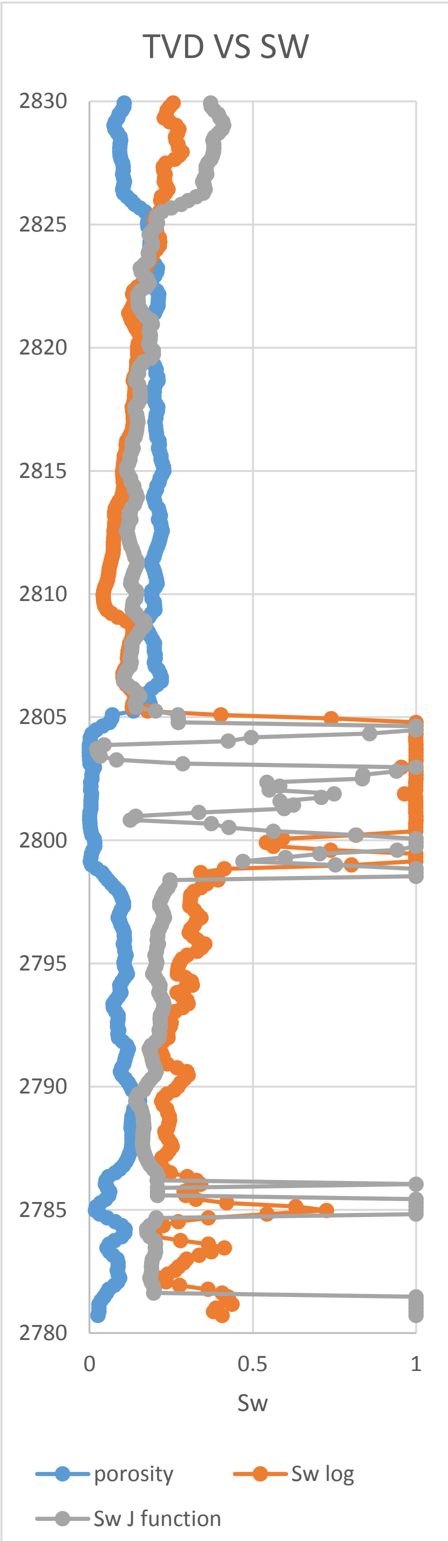


Figure 4.22: Well E2-P5

(Modified J function)

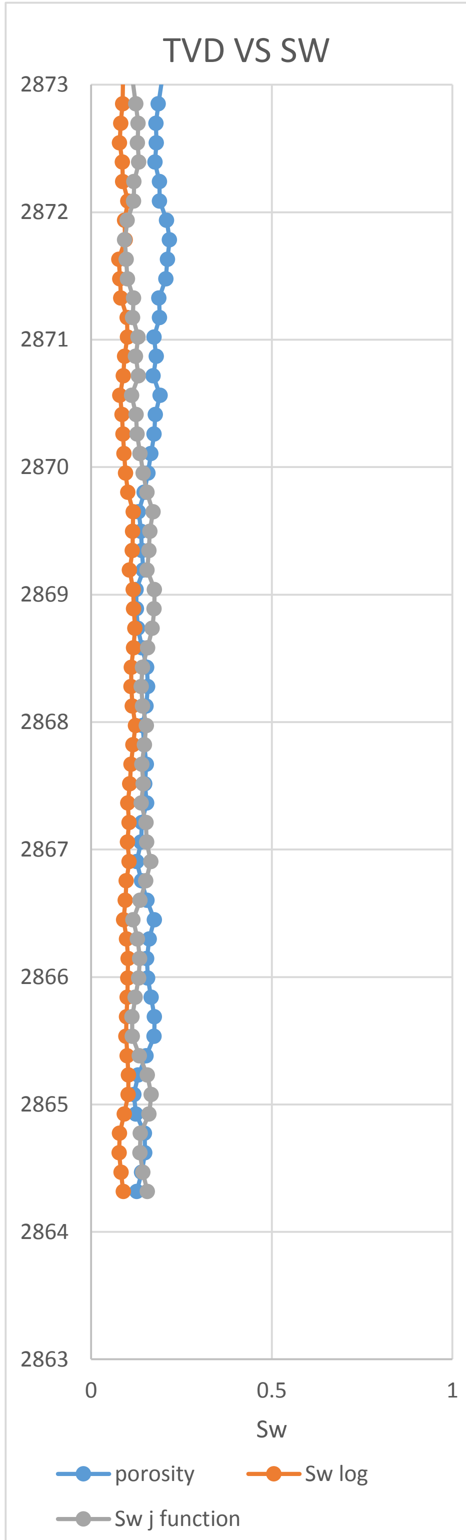


Figure 4.23: well E3-P4

(Modified J function)

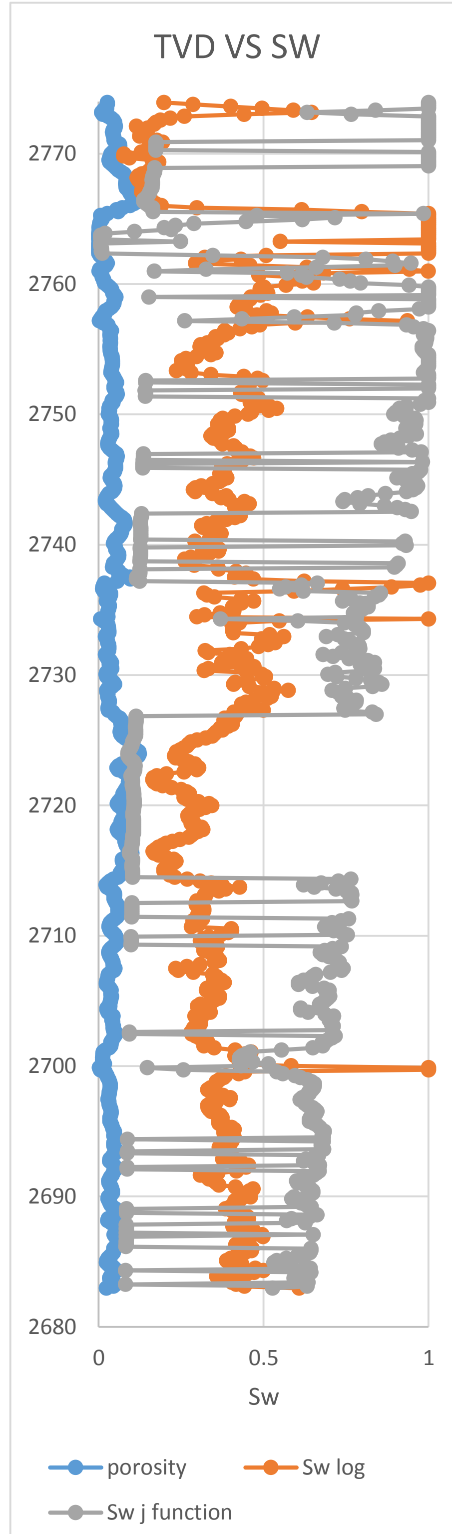


Figure 4.24: well S2

(Modified J function)

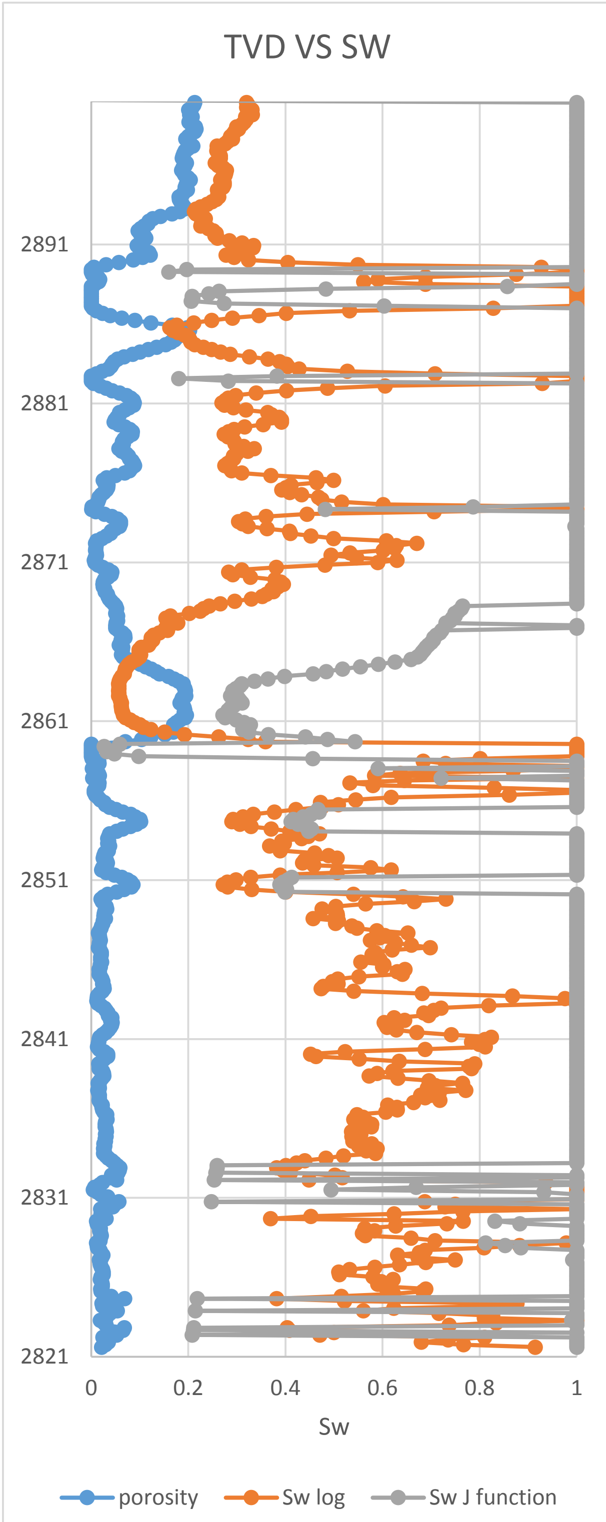


Figure 4.25: Well S6 (Modified J function)

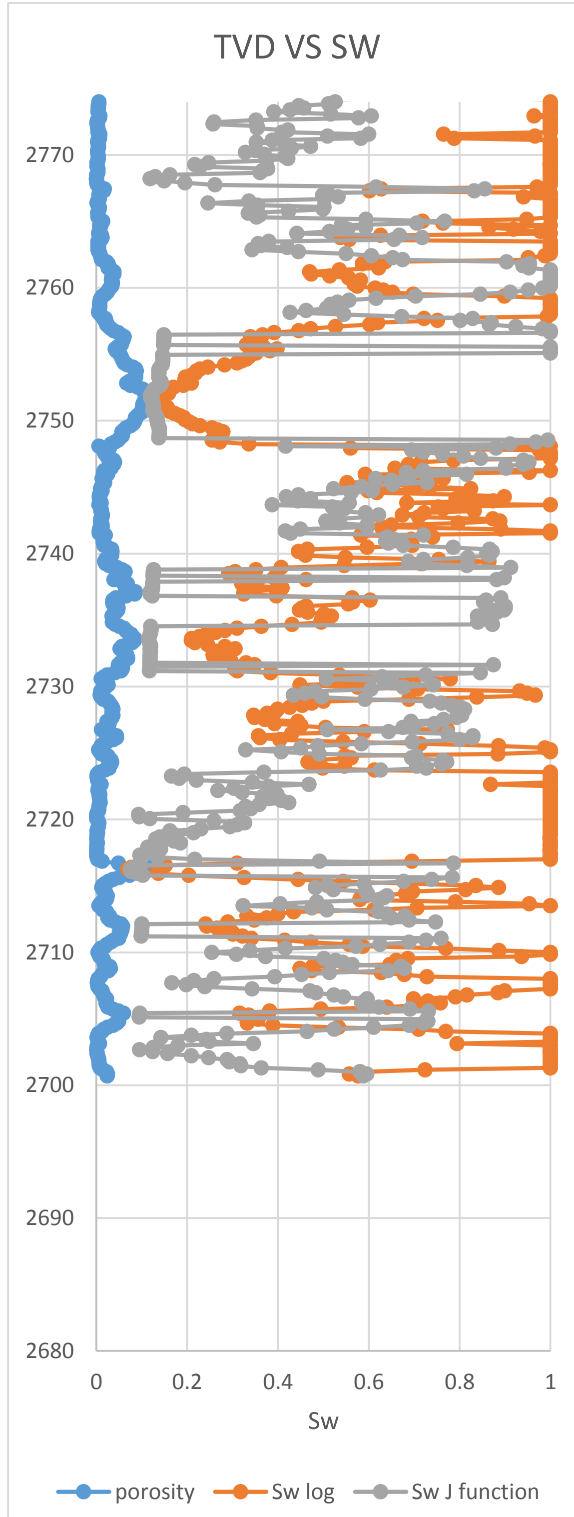


Figure 4.26: Well E1-P4 (Modified J function)

Lambda Function

Lambda – Function is more complex compare to the other two methods mentioned earlier. It is a good way to match the saturation data which is hard to fit with other relationship.

As there are 36 core samples that resulted in a very low connate water saturation, combination of the core samples with almost same porosity and permeability is critical in this part. Figure 4.27 shows the logarithmic value of Permeability to porosity histogram. It is bringing here in order to be able to group the core samples into 4 different set with average permeability and porosity. Table 4.6 shows the lambda constants after grouping based on poroperm histogram.

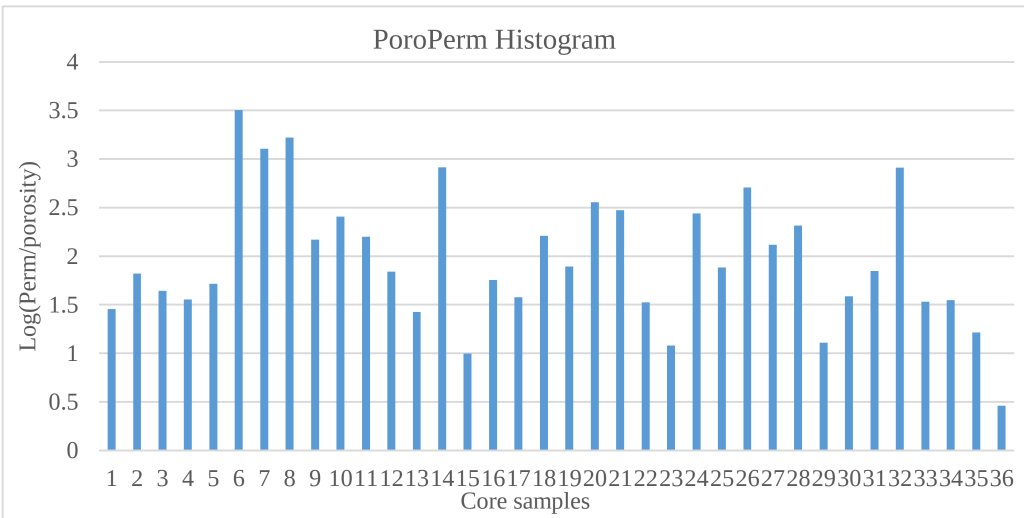


Figure 4.27: Poro-Perm histogram

Table 4.6: Lambda function groups with their properties

Properties	Group1	Group2	Group3	Group4
perm avg	1.594286	7.521429	63.83333	293
poro avg	0.107714	0.145429	0.19025	0.233
A avg	8.612786	8.619829	3.692108	0.4032
B avg	-0.76157	-0.9	-1.12783	-1.32767
A_L	16.90103	10.95073	3.18403	0.504519
B_L	-1.31307	-1.11111	-0.88666	-0.7532
RQI	3.847215	7.191596	18.3173	35.4614
SWC	0.0625	0.0505	0.0434	0.01317

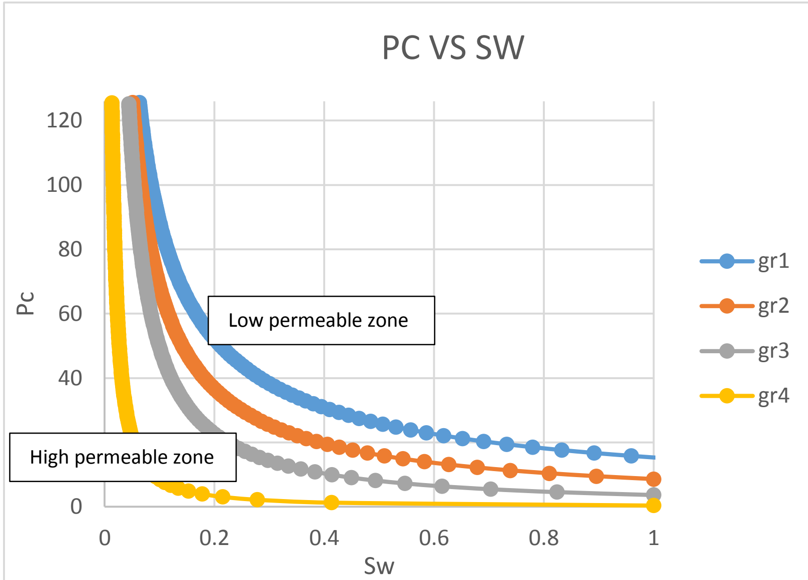


Figure 4.28: Capillary pressure vs water saturation for new 4 different groups

In the figure 4.28 shown, group 4 has the highest permeability and porosity and lowest connate water saturation (Swc) followed by group 1 with the lowest permeability and porosity with the highest connate water saturation (Swc). Based on the result showing in the (table 4.6) the maximum value of connate water Swc is 0.0625 from group 1 which is still a small value for Swc.

Equation 2.3 and 2.4 mentioned in the literature used to estimate water saturation using lambda function.

$$\mathrm{Sw} = \mathrm{A_L} * \mathrm{HAFWL}^{-\lambda} + \mathrm{B_L}$$

$$\lambda = \frac{\log(\frac{\mathrm{A_L}}{\mathrm{Sw} - \mathrm{B_L}})}{\log \mathrm{HAFWL}}$$

After computing lambda for all the 36 core samples, A_L, B_L and λ are plotted against permeability as shown in figure 4.29. These plots are presented in order to get the best fitting and compute 4 sets of constants as A_L, B_L and λ as they shown in table 7.

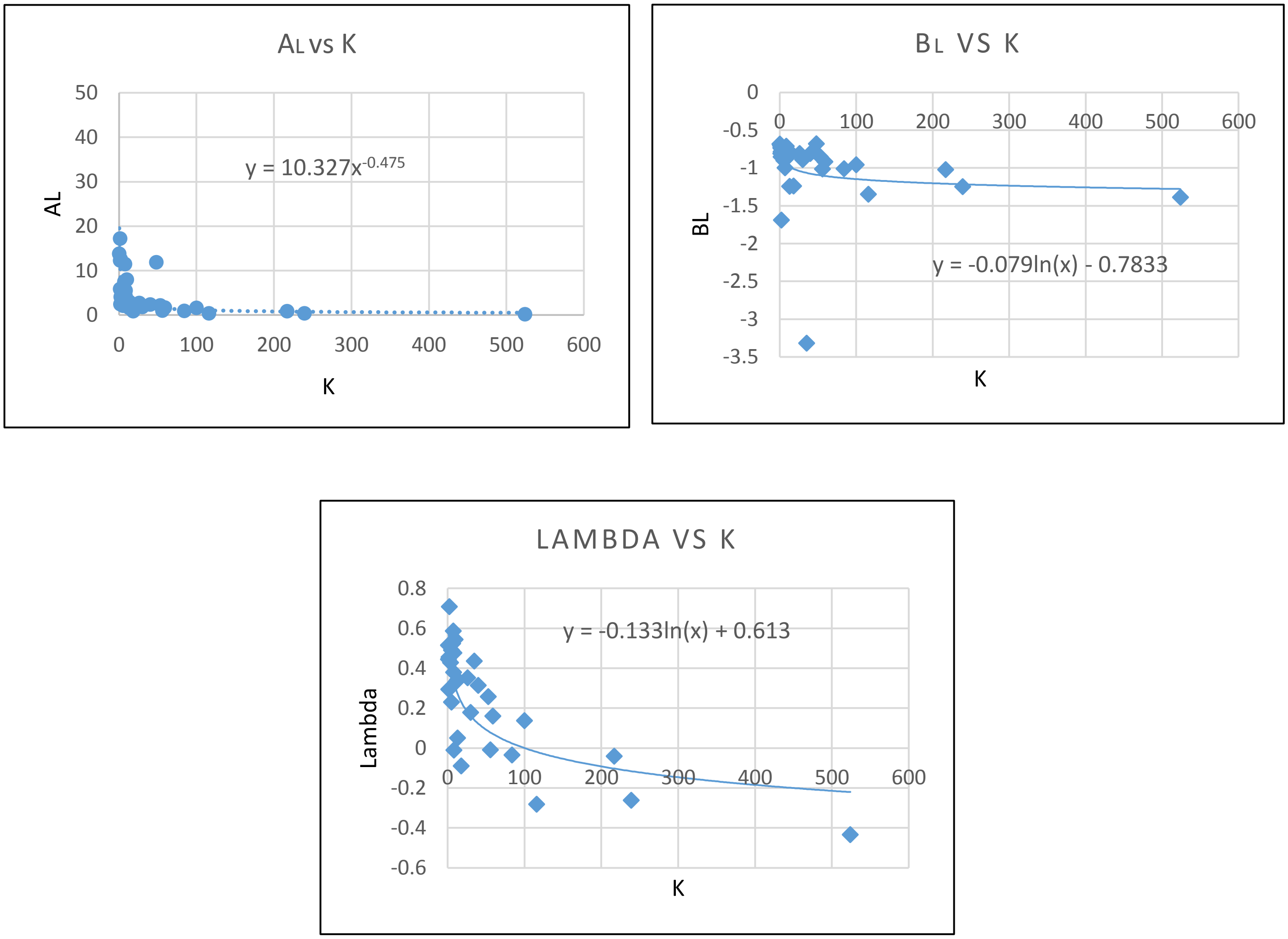


Figure 4.29: A_L, B_L and λ vs permeability

$$\mathrm{A_L} = 10.327\mathrm{k}^{-0.475} \tag{4.6}$$

$$\mathrm{B_L} = -0.079\ln(\mathrm{k}) - 0.7833 \tag{4.7}$$

$$\lambda = -0.133\ln(\mathrm{k}) + 0.613 \tag{4.8}$$

Figures 4.30, 4.31, 4.32, 4.33, 4.34, 4.35 and 4.36 show the Lambda function results for seven wells as follow: well E2-W5, well S6, well E1-P4, well E3-P4, well E2-P5, well S2, well E2-W7.

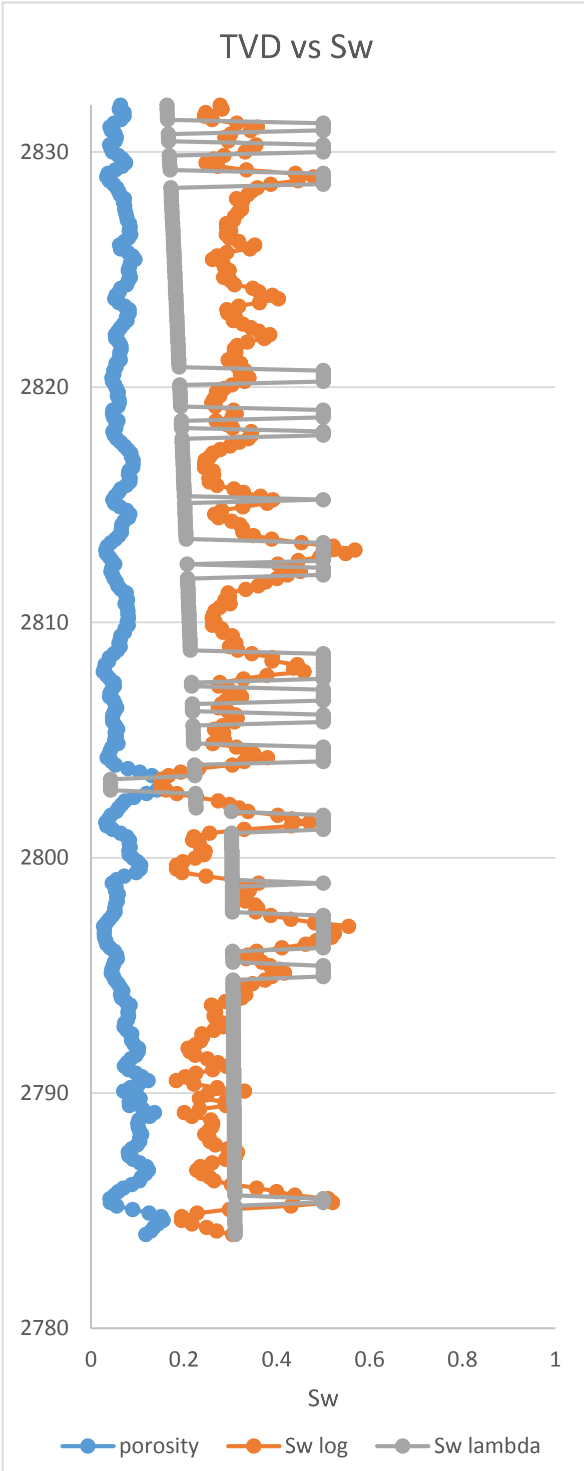


Figure 4.30: well E2-W5

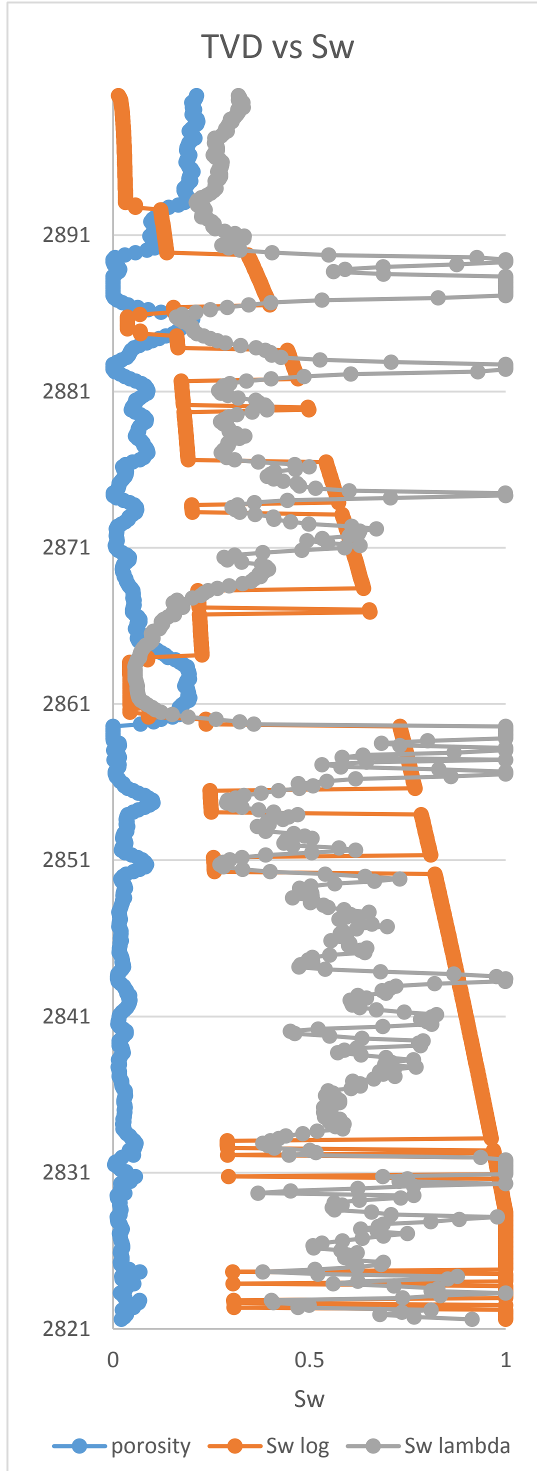


Figure 4.31: well S6

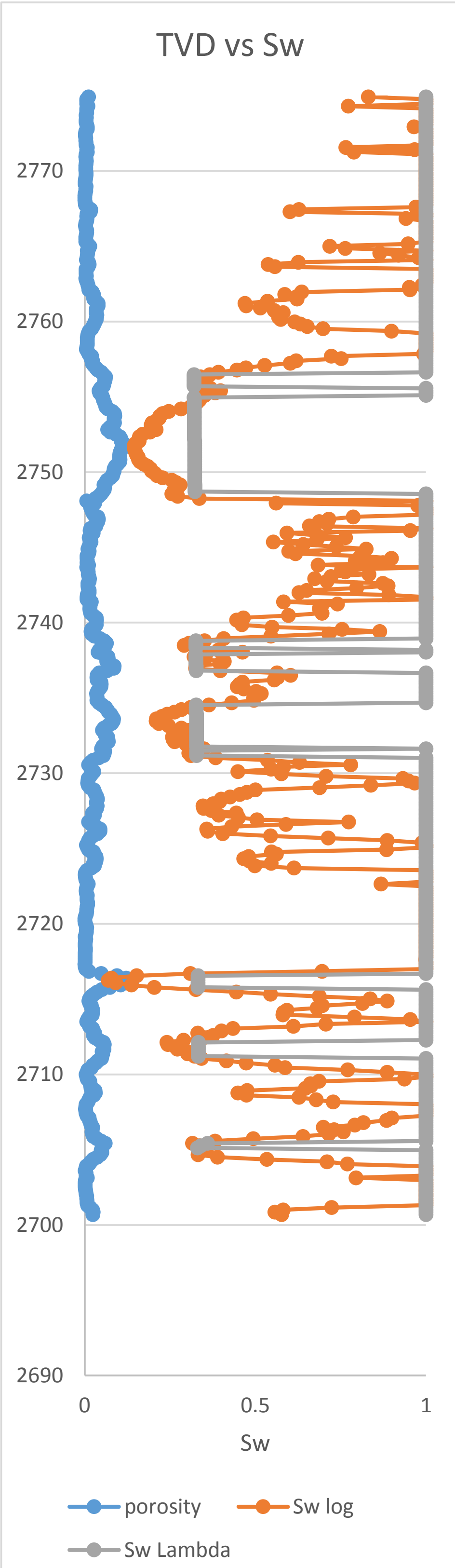


Figure 4.32: well E1-P4

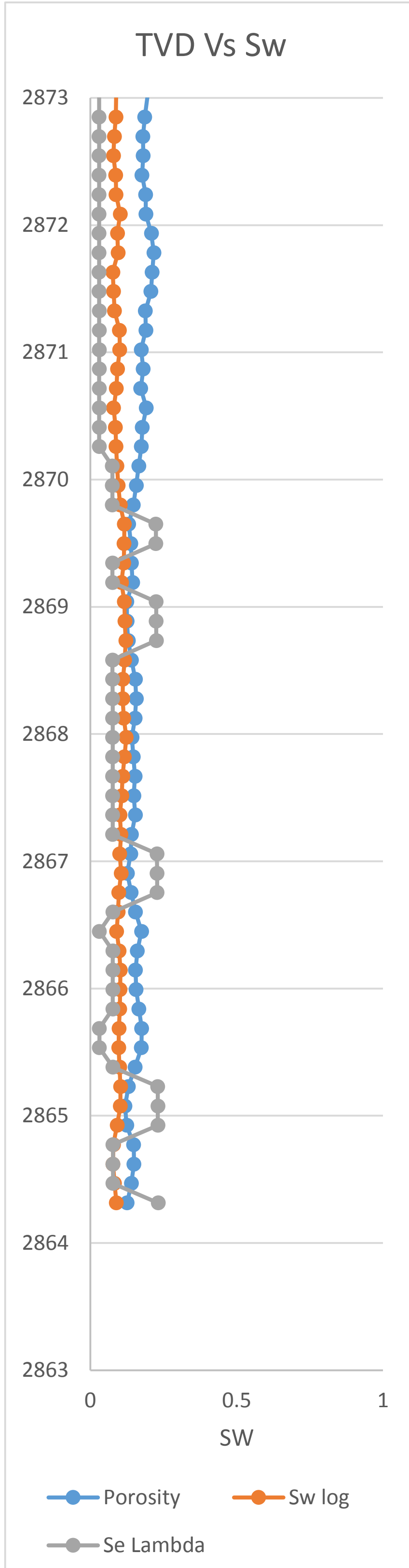


Figure 4.33: well E3-P4

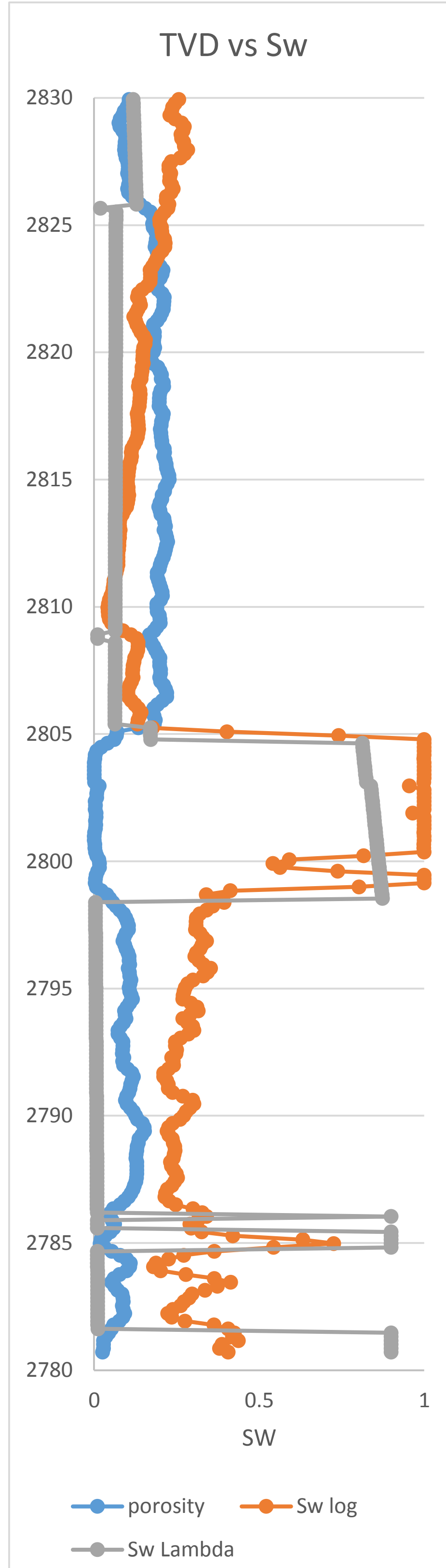


Figure 4.34: well E2-P5

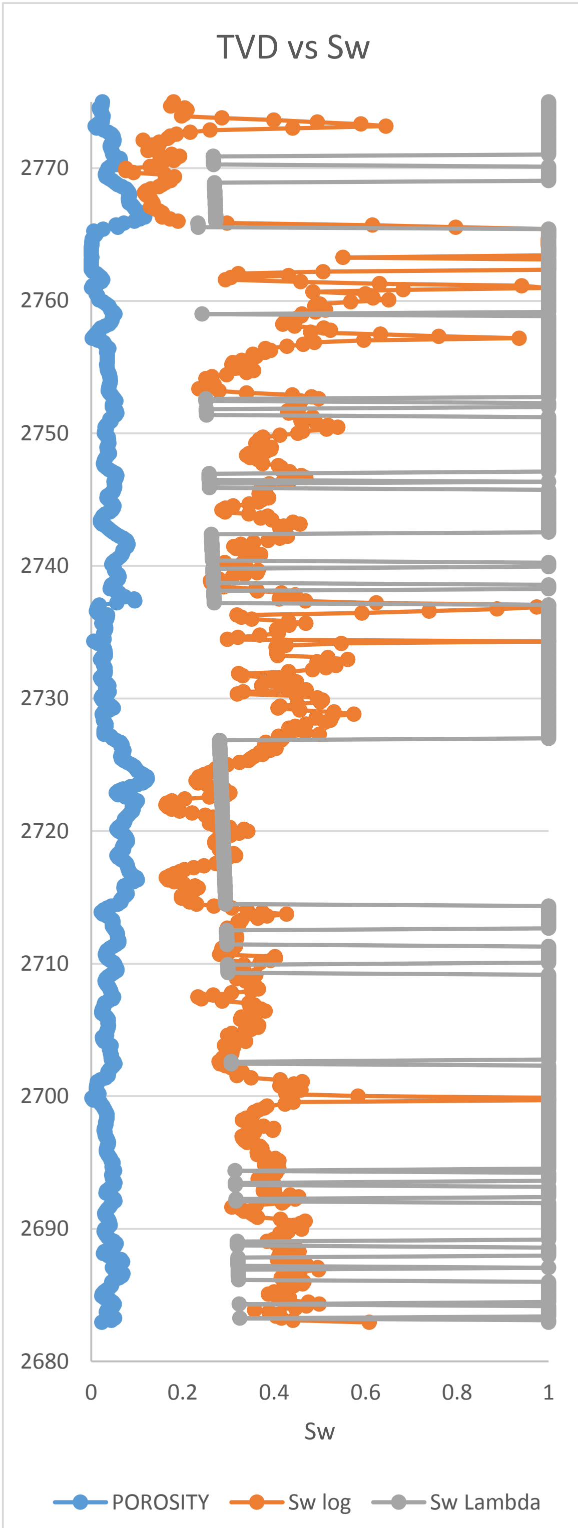


Figure 4.35: well S2

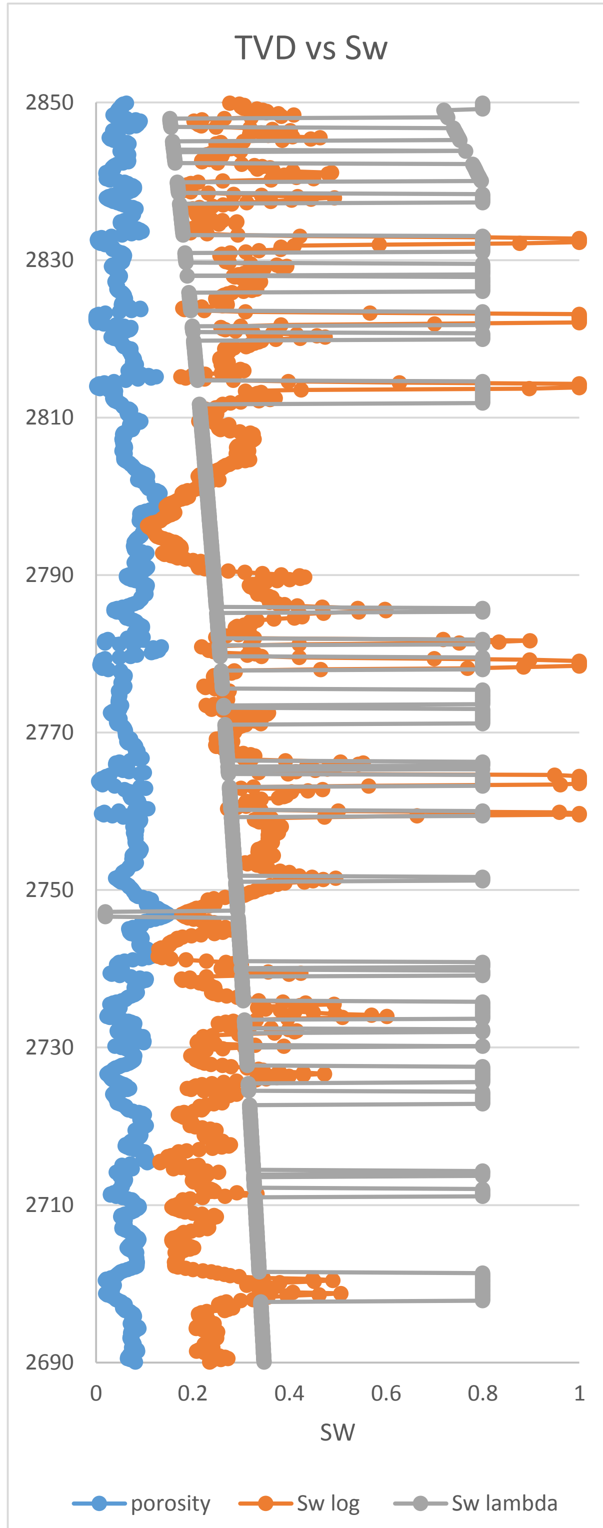


Figure 4.36: well E2-W7

Average absolute percentage deviation (AAD%) and standard error of estimate (SEE)

To elaborate on the accuracy of each method, average absolute deviation **(**ADD) and standard error of estimate (SEE) computed for three SHF methods. The goal of using these equations is to make the comparison between saturation obtained from cores and logging for each SHF. The result of these error tabulated on table 4.7.

Table 4.7: Average Absolute Deviation (ADD %) and Standard Error of Estimate (SEE)

Well\Methods	Modified J-Leverett		J-Leverett		Pseudo-J		Lambda	
	ADD%	SEE	ADD%	SEE	ADD%	SEE	ADD%	SEE
Well E1-P4	68.07	0.429	78.06	0.589	50.25	0.207	63.48	0.204
Well E2-P5	41.07	0.233	48.09	0.343	17.93	0.113	62.58	0.646
Well E2-W5	26.44	0.379	34.41	0.482	20.71	0.09	32.15	0.481
Well E2-W7	70.02	0.275	83.02	0.290	42.54	0.219	56.69	0.221
Well E3-P4	39.75	0.041	78.75	0.241	21.62	0.025	60.69	0.069
Well S6	89.67	0.523	92.64	0.622	56.26	0.386	46.84	0.222
Well S2	73.34	0.423	85.35	0.563	47.13	0.218	84.25	0.509

As it shown in table 4.7, ADD% for the well E2-W5 (modified J-Leverett) give the best match with the lowest ADD% compare to the other wells. In addition well S6 give the worst match and the highest ADD%. For lambda function, E2-W5 give the best and S2 give the worst match results. The ADD% and SEE result, for Pseudo-J method is significantly reduce from the J- Leveret and Lambda function. Based on table 4.7 wells E2-P5 and E2-W5 give the lowest standard error and average absolute deviation. In addition well S6 give the worst match and the highest ADD% and SEE compare to the rest.

In addition the comparison between all the three methods for each well have been shown in the figures 4.37, 4.38, 4.39, 4.40, 4.41, 4.42, 4.43.

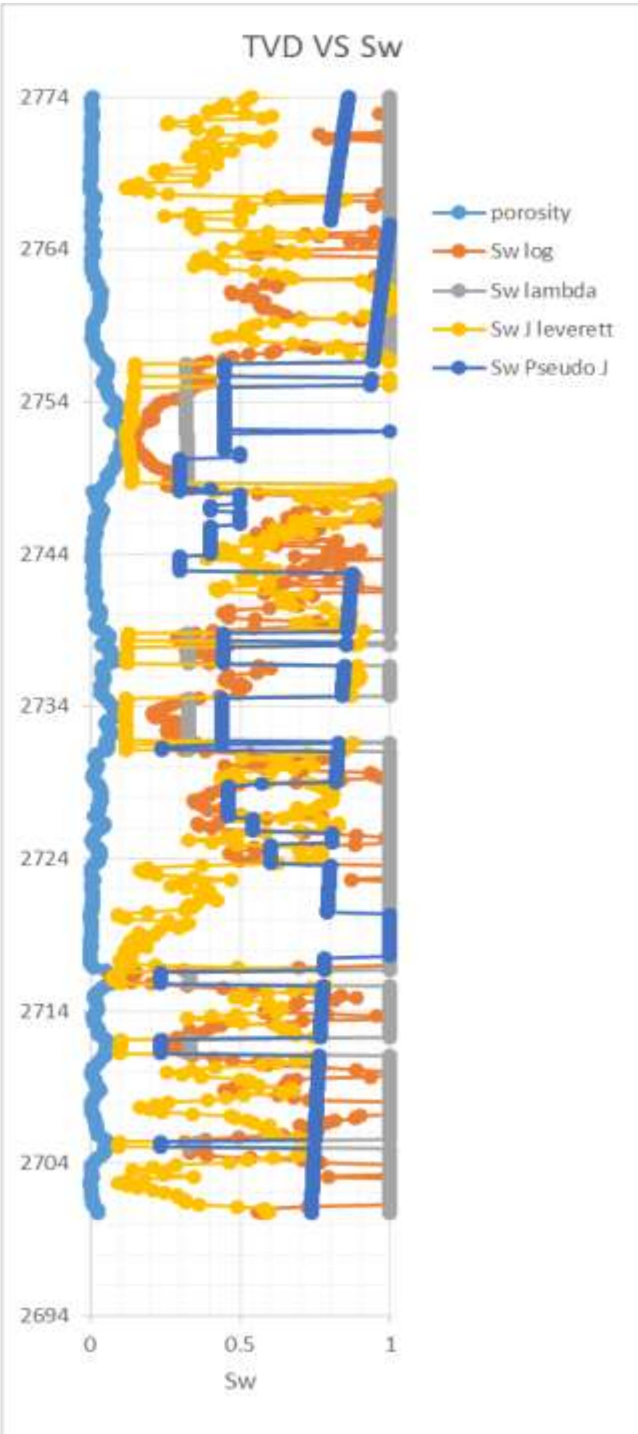


Figure 4.37: well E1-P4

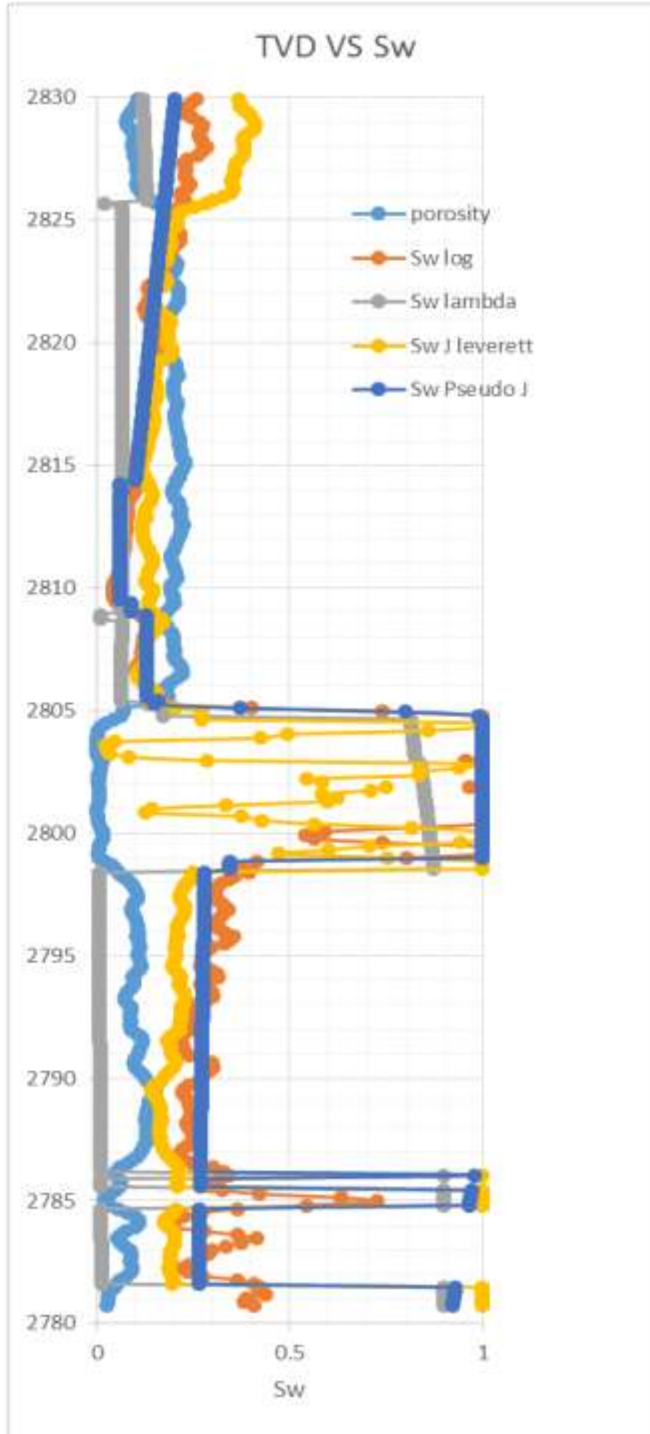


Figure 4.38: well E2-P5

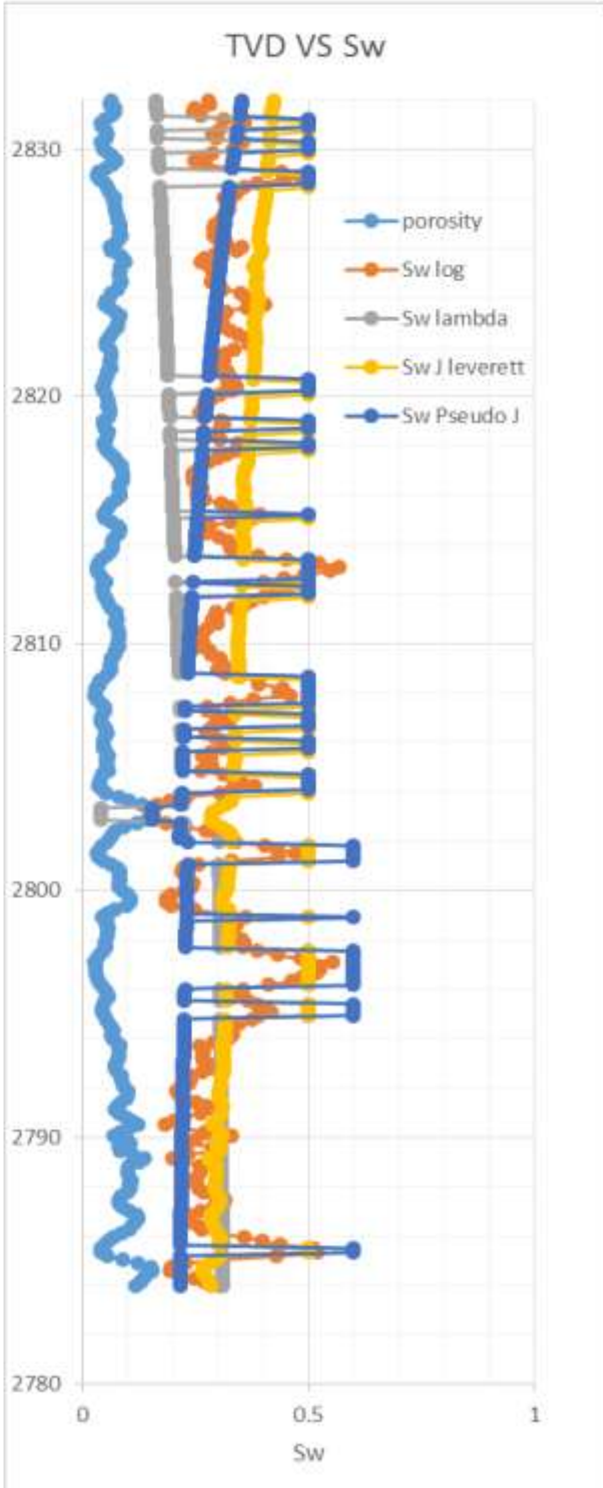


Figure 4.39: well E2-W5

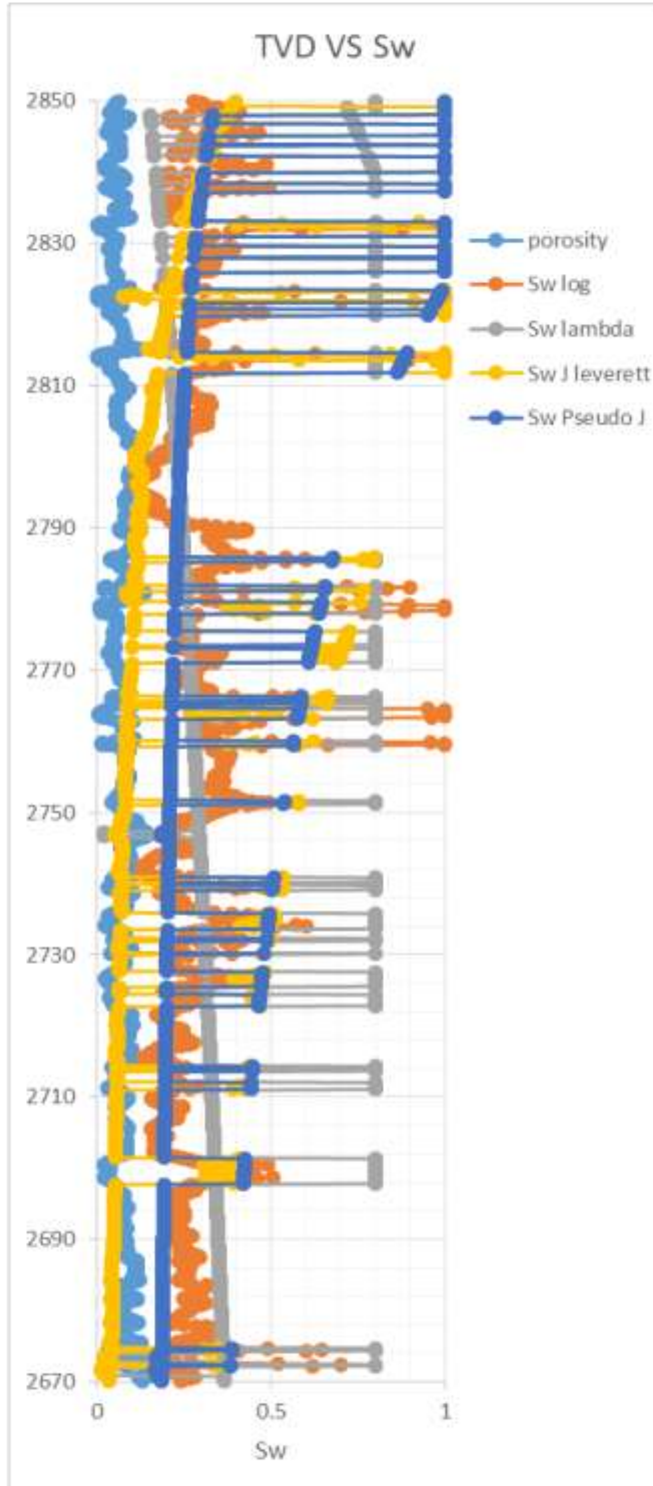


Figure 4.40: well E2-W7

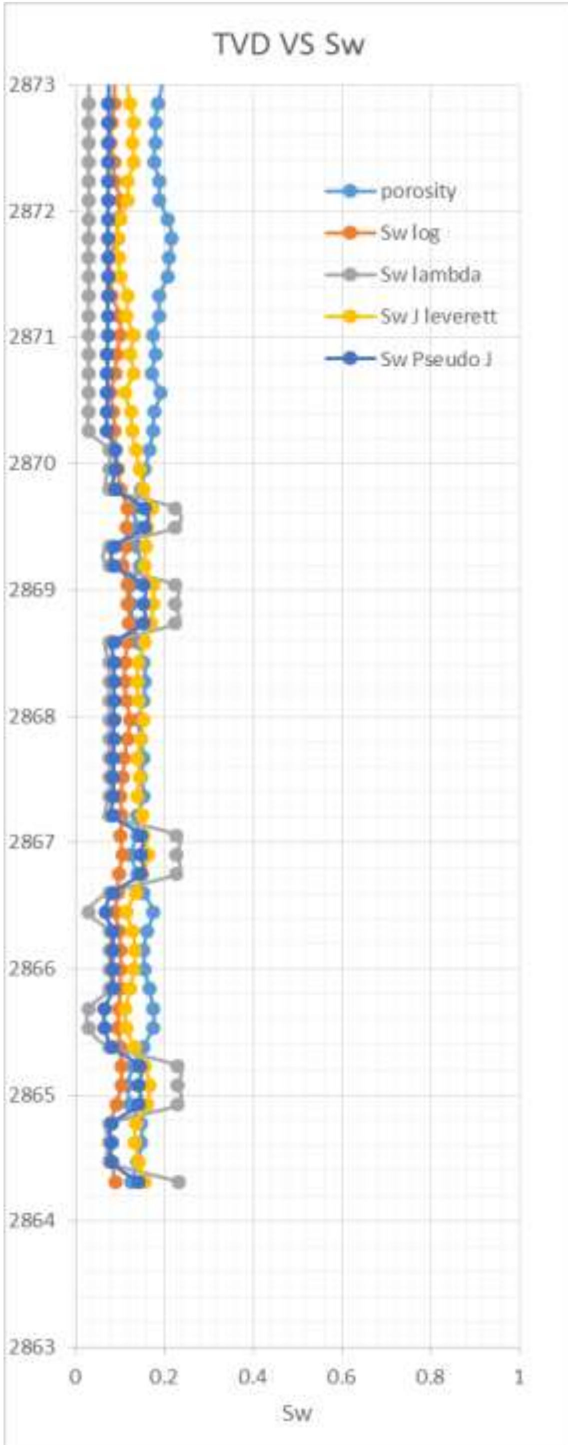


Figure 4.41: well E3-P4

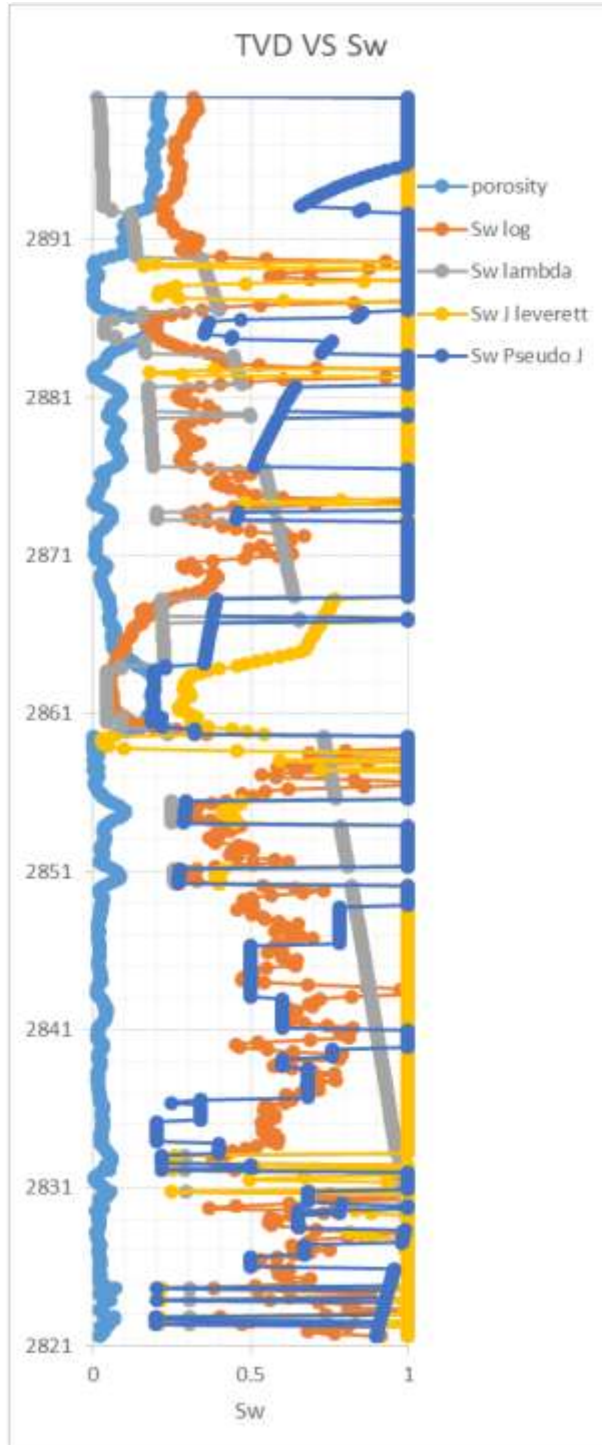


Figure 4.42: well S6

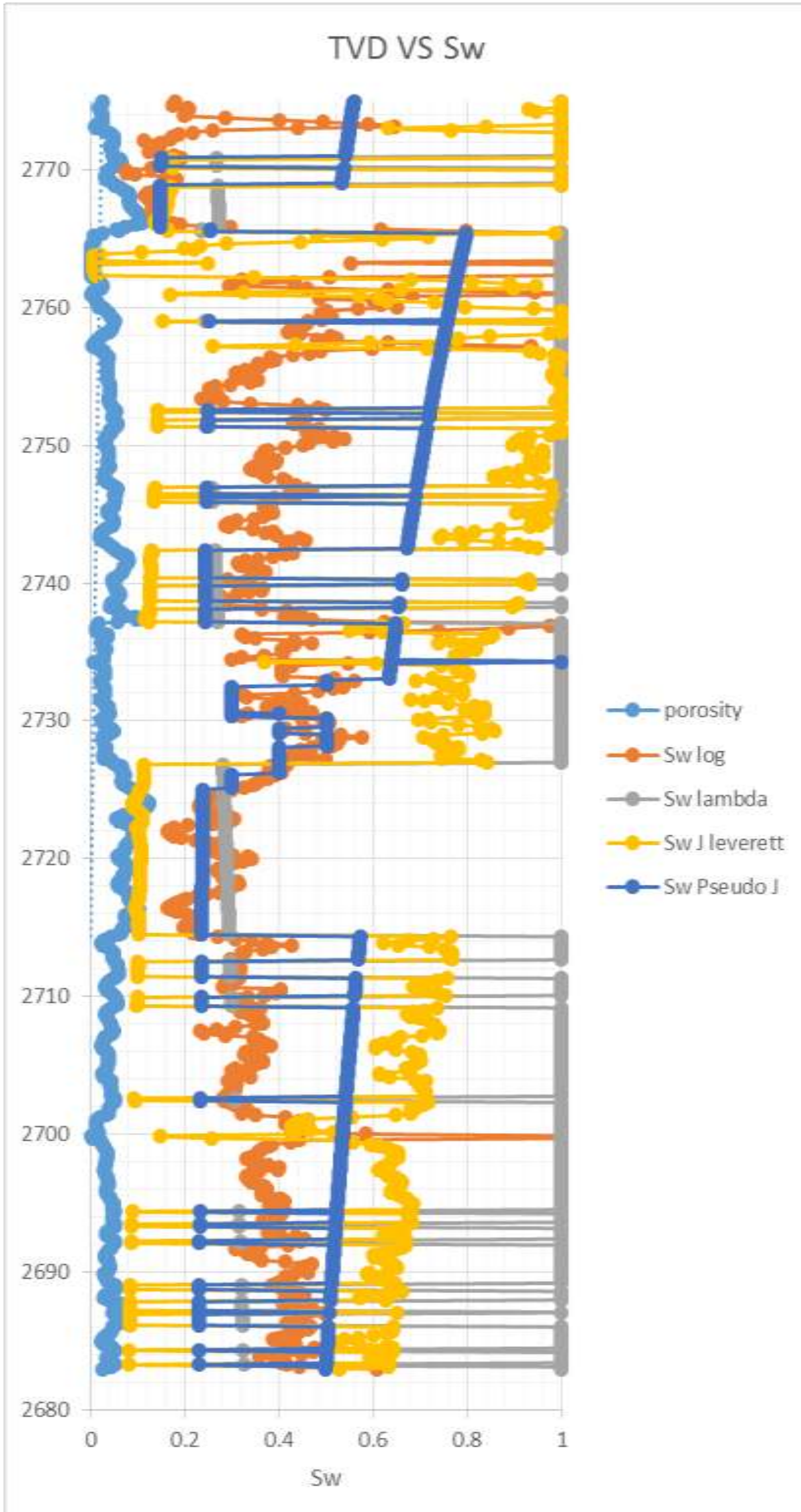


Figure 4.43: well S2

CHAPTER 5

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Log and core analysis are 2 main sources to characterize the reservoir. Water Saturation can be calculated from resistivity log in the wider interval compare to the core however it is essential to consider the limitations in log measurements and interpretation. Complications in log measurement can be due to different factor such as water imbibition processes, clay excess conductivity, mud filtrate invasion and determining of the Archie saturation exponent "n" that is wettability dependent during imbibition process (B. Harrison, 2001). Core analysis provide more accurate result only for certain depths and the measurement need to upscale to analyze the saturation result in wider interval. By these definition, it can be conclude that cores and log data should be integrated in order to give more accurate result about the reservoir. Saturation-height functions used in this study to integrate the result of saturation from core and log. In term of availability of both core and log data, SHF methods can reduce the error encountered from log data by calculating the saturation from the core and comparing its result with log. SHF methods are significant in oil and gas industry since slightly change in capillary pressure curve can affect the reserve estimation.

The objectives of this project achieved successfully. The performance of three SHF methods (J-Leverett, Lambda and Pseudo-J function) evaluated on one of the Iranian oil field. The necessary modification perform on the methodology used in J-Leverett method to improve the result. Modified J-Leverett function consider different curves with respect to permeability and porosity variation and it resulted to give better result compare to the single curve J-leverett. Based on the result shown, this modification resulted in getting less ADD% and SEE followed by getting more accurate hydrocarbon in place result.

In addition new saturation height function as Pseudo-J method introduced in this study and for this oil field under investigation, this method is the best option.

In J-Leverett function, finding Poro-Perm ratio is significant in calculating the J function from Pc. In other word, J-Leverett method uses rock quality index (RQI) to divide the reservoir into different bins. This method will not give a good result in this case study when all the Pc curves are normalizing to be a universal curve that represent all the reservoir. It's mainly because of the permeability, porosity and wettability effect which have significant effect on J-function calculation. To overcome this issue, author changed some procedure in this method in order to improve the results. Modified J-Leverett function consider different curves with respect to permeability and porosity variation and it resulted to give better result compare to the single curve J-leverett. Compare to the J-Leverett method which used RQI, Lambda function used permeability grouping. After visualizing and analyzing the results for each well, it can be conclude that Lambda function is not a good option for this case study. In this study permeability to air is used while klinkenberg permeability normally gives better results. However due to lack of $K_{klinkenberg}$ data availability, K_{air} was the best option. As well connate water saturation (Swc) has significant effect on lambda calculation. In this case study due to the high pressure mercury measurement, the result of Swc is very low and it can be one of the reason that lambda is not giving the best result.

Compare to the other two methods mentioned earlier, Pseudo-J function gives the best match result. The reason is because this method only use porosity variation in its calculation and porosity result is more reliable compare to the permeability and RQI. However Pseudo-J function used porosity binning only while J-leverett used RQI and lambda used permeability. The ADD% and SEE result, for this method is significantly reduce from the J- Leveret and Lambda function.

It can be seen that these results are varying between different wells. This variation in result is due to the stratigraphic location of the wells that effect the saturation calculation. As it mentioned earlier, wells distribution in this field is as follow:

Segment North: E2-W5 and E2-P5

Segment center east: E1-P4 and E2-W7

Segment south west: E3-P4

Segment center west: S6 and S2

Based on this distribution, it can conclude that the wells located in segment north give better result and segment center west give the worst match result. It can be because of the depth interval of each wells as the S6 and S2 are more near to water contact.

5.2 Recommendation

J-Leverett method is the widely used SHF in the industry, however it is important to consider other SHF methods for getting better results. The purpose of this project is to show the usage of different SHF methods and introduce the new SHF as Pseudo-J method that can affect the result of STOIIP and GIIP.

There are other type of Saturation-height methods such as Cap-log, Johnson, Cuddy et al., Skelt Harrison and Sodana (Sohrabi et al., 2007) that can be evaluated in the future studies.

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